ROCKET EXPERIMENTS IN COSMIC MAGNETISM

AND THEIR SIGNIFICANCE

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I. INTRODUCTION

With the exception of the sensible planetary atmospheres and perhaps regions far from stars, much of the gaseous matter of the universe is thought to exist in a partially ionized state. Hydrogen, constituting the bulk of this matter, is considered to provide the primary ingredient from which this ionized medium is formed. In the case of the earth and, presumably, for other planets containing a supply of hydrogenous material of sufficiently low vapor pressure, the far atmosphere, being bathed in the solar far ultra violet, also would consist primarily of ionized hydrogen.

Such regions of ionized gas, called plasmas, have properties sufficiently different from those of gases obeying conventional equations of state that it has been suggested that they be considered a fourth state of matter. One fundamental distinction is that the existence of many free electrons and ions makes Coulomb interactions important. Since this interaction is of long range, the dynamical behavior of such a medium is considerably different from either the ideal or Van der Wals gas. Linhart[1] has pointed out that by extrapolating the energy domain

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1. Linhart, J. G., Plasma Physics, Interscience Publ. Inc., New York (1960).

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of existence of plasmas to extreme values, a counterpart nuclear plasma or "nugas" and even a highly relativistic free meson - nucleon - electron plasma should exist. It seems reasonable, in fact, to consider the primary cosmis radiation over sufficiently great distance scale as constituting this relativistic plasma.

It has often been argued that plasmas of astrophysical scale can be shown to be electrically neutral over distances large enough to average out fluctuations.[2] The electrical neutrality, or what is equivalent, the absence of free charge, implies that $\nabla \cdot D = 0$. This condition is violated for frequencies where displacement currents are important and radiation fields exist. For the subject of hydromagnetics, the frequencies are taken so low that $\partial D/\partial t \sim 0$. Violation of this condition may be considered as the transition from the discipline of hydromagnetics to that of radio astronomy.

Because of the physically important implications when magnetic fields and plasmas are mixed, their combined existence is a fundamental subject in the field of astrophysics. Until 1928, the only large-scale natural magnetic field known was that of the earth. In that year, Hale demonstrated

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2. Alfven, H., Cosmical Electrodynamics, Oxford Univ. Press (1953).

spectroscopically the existence of fields of some thousands of gauss associated with sunspots. In 1946, Babcock at Mt. Wilson reported a 1500 gauss field component about the star 78 Virginis, and today the list of such stars is much extended. Indeed, radio astronomical observations of the galactic halo strongly support the idea that the continuum radiation noted at radio frequencies is from synchroton emission which requires a magnetic field for its generation.[3]

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3. Shklovsky, I. S., Cosmic Radio Waves, p. 191, Harvard Univ. Press, Cambridge, Mass. (1960).

The discovery of the polarization of starlight by Hiltner, Hall, and Mikesell[4, 5] in 1949 has lent support to the notion of

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4. Hiltner, W. A., On the Presence of Polarization in the Continuous Radiation of Stars, Ap. J. 109, 471 (1949).
5. Hall, J. S. and A. H. Mikesell, Observations of Polarized Light from Stars, A. J. 54, 187 (1949).

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a spiral arm field in the galaxy, a mechanism of polarization having been supplied by a theory of Davis and Greenstein[6] which

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6. Davis, L., Jr. and Jesse L. Greenstein, The Polarization of Starlight by Aligned Dust Grains, Ap. J. 114, 206 (1951).

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involves alignment of interstellar dust grains.

Recent years have seen the development of interplanetary models, for example, those of Parker,[7] Elliot,[8] Lüst and Schlüter,[9] and Block,[10] all invoking fields for their

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7. Parker, E. N., Solar, Planetary, and Interplanetary Magnetohydrodynamics, Chapt. 8 in Plasma Dynamics, F. H. Clauser, ed., Addison-Wesley Publ. Co., Reading, Mass. (1960).
8. Elliot, H., Cosmic Ray Intensity Variations and the Interplanetary Magnetic Field, Phil. Mag. 5, 601 (1960).
9. Lüst, R. and A. Schlüter, Kraftfreie Magnetfelder Z f. Astrophysik 34, 263 (1954); also Drehimpulstransport durch Magnetfelderund die Abbremsung rotierender Sterne, Ibid., 38, 110 (1955).
10. Block, L., On the Interplanetary Gas and its Magnetic Field, Ark. f. Fysik 14, 179 (1958).

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completeness. The existence of large-scale fields on the sun in regions away from spots and some characteristics of their behavior has also been established by Babcock and Babcock.[11]

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11. Babcock, H. W. and H. D. Babcock, The Sun's Magnetic Field, 1952-54, Ap. J. 121, 349 (1955).

Today, on the scale of the earth's magnetosphere, in

interplanetary space and in interstellar space beyond, there are compelling arguments for the existence of magnetic fields and for their importance in the dynamic makeup and history of the universe.

Looked at from the standpoint of astrophysics, rockets are a new tool available for directly studying problems in astronomy unencumbered by the body or atmosphere of the earth. The opacity of the earth's atmosphere to the far ultra violet is a well-known and non-trivial constraint upon optical astronomy. The high atmosphere or exosphere of the earth with its magnetic field is a qualitatively similar barricade to propagating interplanetary phenomena though here, transmission, albeit highly modified, does occur.

This chapter will deal with some of the principal results of the experimental complement to cosmic electrodynamics, the direct observation of magnetic fields and plasmas in space which have been made since the first lunar orbiter attempt some three years ago. This research program is in its infancy; a number of observations bearing on the structure of the outer gaseous mantle of the earth have been made, though the number of unsolved problems appears to have increased since the first experiment on Pioneer I.

The discussion will consider some measurements of the interplanetary field and their relation to theoretical models. Then we shall consider briefly the interaction of the earth with

both the undisturbed and storm time interplanetary medium. Certain aspects of the interplanetary medium as well as the detailed discussion of certain phases of the geophysical resultant of interplanetary storm-earth interaction such as ring currents will be dealt with in other lectures.

The breadth of the fields of geophysical and interplanetary hydromagnetics is so great that no claim for completeness can be made for this review, which is necessarily limited to material directly relevant to certain experiments. A strong case is made for consideration of plasma data as well as magnetometer data and so comments are included on both.

In this country, the principal efforts to the time of this writing have been in magnetic fields, though interest is increasing in the area of plasmas. The principal efforts in magnetic fields have been conducted by the author and coworkers while at Space Technology Laboratories and by Heppner and associates at Goddard Space Flight Center. Plasma measurements have been made by Bridge and colleagues at MIT, by Bader at Ames Research Center, and experiments unfortunately terminated by rocket failure have been attempted by Snyder and Neugebauer at JPL. Russian magnetometer data is considered, though spacecraft fields in these instances have high thresholds so that interplanetary measurements generally provide only upper bounds. Plasma probe data is more complete and, indeed, a large portion of available information seems to have come from the U.S.S.R.

II. SOME CONDITIONS ON ASTROPHYSICAL PLASMAS

There are certain characteristics of cosmic plasmas which make them distinctive from laboratory plasmas. These are principally charge neutrality and the collisionless condition except, perhaps, in the interior or neighborhood of stars. Thus, to some extent, even long-range Coulomb interactions are secondary in importance as compared to the effect of the magnetic field. The latter, in effect, replaces electrostatic interactions, and one finds that the dominant length is the Larmor radius. Collisional rearrangements leading to the establishment of well-behaved Boltzmann distributions become inoperative, and dynamical perturbations do not necessarily lead to equilibrium states, i.e., the velocity distributions are anisotropic and electron and proton energies may be non-Maxwellian.

The most important forces which operate on a cosmic plasma are those provided by electric fields, magnetic fields, pressure gradients and inertial accelerations (including gravity). Particle collisional effects are, as discussed above, usually ignorable in interplanetary and interstellar space and often in planetary exospheres. Then the equation of motion (Newton's 2nd Law) becomes[12]

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12. Spitzer, L., The Physics of Fully Ionized Gases, p. 18; Intersciences Publ. Inc., New York (1956).

$$m\left(\frac{d\vec{v}}{dt}\right) = e\left(\vec{E} + \vec{v} \times \vec{B}\right) - \nabla \cdot \chi - m\vec{a} \qquad (1)$$

where m is the particle mass,

$$\frac{d}{dt} \text{ means } \frac{\partial}{\partial t} + v \cdot \nabla$$

$\nabla \cdot \psi$ is the divergence of the stress tensor (the pressure gradient for zero shear) and a is the net acceleration due to inertial forces.

Together with the equation of continuity, $\nabla \cdot (\rho v) = 0$ and Maxwell's equations taken with the special conditions that free charge and displacement currents are zero, Eq. (1) forms the framework in which much of the subject is cast. A more formal approach using the Boltzmann equation reduced to Liouville's theorem (invariance of the distribution function in phase space for no collisions) is often employed. Eq. (1) is obtained from it by integrating the Boltzmann equation over velocity space having first multiplied through by the momentum.

Of importance in non-relativistic cosmic electrodynamics is the velocity transformation of fields. When $v/c \ll 1$ the magnetic field transforms into itself. As a consequence of the high conductivity for the observer moving with a cosmic plasma, no electric field is seen. In coordinate systems having relative motion with respect to the plasma, an electric field is

displayed, given by E = -V x B where V is the relative velocity with respect to the plasma. More generally, i.e., for large but finite conductivity (σ) and under the above conditions, an electric field of reduced value is seen. The "freezing in" of lines of force to the plasma for the case of infinite conductivity (in effect a consequence of Lenz' law) is modified in the case of $\sigma < \infty$ by diffusion of the field through the plasma. This is seen as follows: Assume a gyrotropic plasma having associated with it a velocity field (with respect to a frame, O) given by v, where $v/c \ll 1$, and an electromagnetic field, $\vec{E}$, $\vec{H}$, where $\vec{E}$, $\vec{H}$ is measured in the frame of reference in which the plasma displays the velocity field, $\vec{v}$ (namely O). Further, for simplicity, assume a finite, scalar[13] conductivity.

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13. Biermann, L., Stellar Atmospheres as Plasmas, Nuovo Cimento, 13, Ser. X, 189 (1959).

Then in the frame of the plasma the field vectors transform into ($\vec{E} + \vec{V} \times \vec{B}$, $\vec{B}$) and any current which flows is given by

$$\vec{j} = \sigma(\vec{E} + \vec{V} \times \vec{B}) \tag{2}$$

Since Maxwell's equations are invariant to this transformation, in the plasma frame

$$-\frac{\partial B}{\partial t} \doteq \nabla \times \vec{v} \times \vec{B} - \frac{1}{\sigma} \nabla \times \vec{j} \tag{3}$$

In the limit of low frequencies $\vec{j} = \nabla \times \vec{H}$ and making use of the appropriate vector calculus, Eq. (3) reduces to

$$\frac{\partial \vec{H}}{\partial t} = \nabla \times \vec{V} \times \vec{H} + \frac{1}{\mu \sigma} \nabla^2 \vec{H} \tag{4}$$

a result given by Cowling.[14] For illustrative purposes, the

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14. Cowling, T. G., Magnetohydrodynamics, Interscience Publ. Inc., New York (1957).

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the two limiting cases of $\sigma \rightarrow \infty$ and of $v = 0$ can be examined. Consider the case where $\sigma \rightarrow \infty$; then the leading term dominates. This corresponds to the condition of extreme conductivity with the velocity field for the plasma being pointwise isomorphic with the velocity field of $\vec{H}$ and corresponds to the geophysically and astrophysically important situation where the field is "frozen" into the plasma. A proof of this is direct. Consider a tube of force forming the cylinder defined by a bundle of lines of force, the end sections being pointwise normal to the lines. Then everywhere on the side surfaces* of the tube, $\vec{B} \cdot \vec{ds} = 0$, the two ends sum to zero, and it follows that

$$\frac{\partial}{\partial t} \int \vec{B} \cdot \vec{ds} = 0 \tag{5}$$

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*By side surface is meant the generatrix of the conic.

everywhere on the surface of the tube. (Eq. (5) is, incidentally, also true for any subsidiary tube of force.) Application of Stokes' theorem to Eq. (3) under the restriction of Eq. (5) then demands that

$$\int \vec{V} \times \vec{B} \cdot \vec{d\ell} = 0 \tag{6}$$

where $\vec{V}$ is measured in the plasma frame. Since $\vec{dl}$ and $\vec{B}$ are non-zero, $\vec{V} = 0$ in this limit.

The situation where the seoond term of Eq. (4) dominates provides an equation of diffusion, for if

$$\frac{1}{\mu\sigma} \nabla^2 \vec{H} \gg \nabla \times \vec{V} \times \vec{H}$$

then

$$\frac{\partial \vec{H}}{\partial t} \sim \frac{1}{\mu\sigma} \nabla^2 \vec{H} \tag{7}$$

Dimensionally one can associate a characteristic time and length from (7) where

$$\tau \sim \mu \sigma L^2 \tag{8}$$

This expression is of fundamental importance in cosmic electrodynamics since it relates the diffusion time of a field out of a

region to a characteristic length. Cowling estimates, for example, for the earth that the field should decay in $\sim 10^4$ years if sources of energy were not present.[15]

15. Ibid., p. 5.

Thus the annihilation of a primordial field should have occurred early in the history of the earth. Also for, say, an interstellar gas cloud where $L \sim 3 \times 10^{19}$ cm, the decay time is $\sim 10^{23}$ years.[16] It is important to recognize that σ need not actually

16. Shklovsky, I. S., p. 182, Ibid.

be comparable to laboratory values. The enormous scale of distance normally suffices to make the apparent conductivity high. Since this discussion is applicable to continuous media, for dimensions comparable to Larmor radii, the theory breaks down. This means, then, that a sharp corner in a field might well diffuse faster than given by Eq. (8). Also, the presence of large amplitude waves or turbulence of scale comparable to the Larmor radius might reduce the time scale of diffusion appreciably.[17]

17. Fishman, F. J., A. R. Kantrowitz, and H. E. Petschek, Magnetohydrodynamic Shock Wave in a Collision-Free Plasma, Rev. Mod. Phys. 32, 959 (1960).

Alternatively, one might consider that the conductivity was lower than calculable from Eq. (8). Nevertheless, the continuum theory has enormous importance, for it enables one to show that for many cases of interest, cosmic fields are a feature of extreme lifetime astrophysically.

The geometry of a tube of force has deeper meaning than the line of force, since one can discuss energy in a manner useful in understanding field stability and dynamic properties. It is not heard to show, directly, from the Maxwell stress tensor for an electromagnetic field,[18] that the magnetic energy density is

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18. Stratton, J. A., Electromagnetic Theory, p. 97; McGraw-Hill, New York (1941).

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given by $\frac{\vec{B}\cdot\vec{H}}{8\pi}$ and that this energy density is equivalent to a pressure tending to distend the field much as if it were a gas. This pressure is anisotropic; that is, it is dependent upon direction with respect to the field. A convenient model shown in Fig. 2 provides an isotropic pressure of $H^2/8\pi$ and a tension along the lines of force tending to shrink the tube length, by $H^2/4\pi$. Simple magnetic configurations such as tubes of force and closed tubes (toroids) which are not twisted in a special manner are all unstable and have no potential minimum.

Plasmas normally exhibit a multitude of oscillatory modes. Spitzer[19] has described those in an electron gas. Without magnetic

19. Spitzer, L., Jr., Ibid., Chapt. 4

field, the low frequency transmission cutoff is given by the plasma frequency, $\omega_p = \left[\frac{4\pi n e^2}{m}\right]^{1/2}$. When a one-component plasma is immersed in a magnetic field, other modes appear. First, the plasma is birefringent, exhibiting an ordinary and extraordinary mode. There will be a mode propagated below the plasma frequency (circularly polarized, extraordinary mode). Electrostatic waves are also allowed; for binary plasmas, both ion and electron waves are present. Binary plasmas exhibit modes of propagation to $\omega = 0$. The hydromagnetic mode is popularly used to signify a group which exist below the ion gyro cutoff. The transverse mode was discovered by Alfven,[20] and bears his name. This mode is in

20. Alfven, H., Ibid.

reality two: circularly polarized, right- and left-handed; and in the low frequency limit the medium becomes monorefringent. Åstrom[21] has discussed the many-component plasma in a magnetic

21. Åstrom, E., On Waves in an Ionized Medium, Archiv. för Fysik 2, 443 (1950).

field and analyzes the allowed modes. Fig. 3 shows the simplest case of transverse waves to illustrate the many stop bands in a polytropic plasma.

Finally, the problem of hydromagnetic turbulence appears occasionally in the data. For the purposes here, a detailed definition of this phenomena, seemingly unresolved, is not needed. What is of importance are the energy densities of gas and field, that is to say, which is in dynamic control? If the former, we would expect that the field would "wrinkle" and become disordered in direction as a result of motions in the gas. The lifetime of magnetic eddies resulting from annihilation of opposed tubes of force is unknown now. For the case of field control, the consequences seem more straightforward as then plasma motion is governed by the dominant field and follows the usual rules for charged particles in fields.

III THE OUTER ATMOSPHERE OF THE EARTH

Prior to Storey's analysis[22] of some unusual radio signals

22. Storey, L. R. O., An Investigation of Whisting Atmospherics, Phil. Trans. Royal Soc. 246, 113 (1953).

of a type first observed by Barkhausen in World War I, it was generally held that the earth had an exosphere, a region beyond the ionosphere, in which collisional effects were so sparse because of the low density that gas molecules executed free ballistic motion. This was in keeping with an escape rate dependent upon temperature. In one sense, this model was not even fluid dynamical; in any event, it provided no coupling to the geomagnetic field, for the total gas body was taken to be non-ionized. The analysis of Storey profoundly modified exospheric models since he demonstrated that the propagation characteristics of the signals which he analyzed demanded an electron gas of $10^2 - 10^3$ cm^{-3} density. An immediate consequence, as recognized by Dungey,[23] was that the usual requirement of cosmic electro-

23. Dungey, J. W., Electrodynamics in the Outer Atmosphere, Physics of the Ionosphere, pp. 229-236 (1955); publ. by Phys. Soc. of London.

dynamics of no free charge, i.e., $\nabla \cdot D=0$, required an

ion-electron atmosphere of pointwise charge neutrality. Today we recognize the exosphere or, as it has more recently been called, the magnetosphere,[24] as a body of gas bounded on its interior

24. Gold, T., Plasmas and Magnetic Fields in the Solar System, J. Geophys. Res. 64, 1665 (1959).

surface by the non-conducting atmosphere and on its exterior surface by electrodynamic coupling between it and the interplanetary gas in some manner not well understood. The general shape of the magnetosphere may approximate the dipolar field equatorially; there is presently some evidence that a solar-antisolar asymmetry exists due to unequal pressure gradients. The polar field at extreme altitudes is the subject of conjecture; the connectivity to the interplanetary field is unknown. Since the polar axis is a null line of the field, an apparent surface current singularity might exist where the polar null line intersects the boundary (assumption of a Chapman-Ferraro boundary is made in this instance).

The connectivity of the geomagnetic field to the interplanetary volume has suggested that exchange of angular momentum might brake the rotational velocity of the earth appreciably in geological times. However, paleomagnetic evidence of magnetic polar wander accompanied, perhaps, by spin

pole wander make any surmises hypothetical. The extent of geopolar-interplanetary field tangling as a primary means of exchange of angular momentum with "frictionless" slipping in non-polar regions remains to be investigated.

A. Current Systems

Quite generally, the magnetosphere is an electrodynamic medium, both inhomogeneous and anisotropic, containing the Van Allen belts, large-scale currents and perhaps, other, as yet uncovered, phenomena. This body of gas, in effect, provides us with an earth-centered astrophysical gas cloud, having primarily magnetofluid behavior, close at hand, which can be studied with broad band telemetry and high information rate instruments for a better understanding of astrophysical behavior as it takes place in the universe at large.

The physical behavior of the magnetosphere is governed by the distribution of plasma, consisting primarily of protons and electrons, the configuration of the magnetic field, both that generated in the core of the earth and locally generated fields in the high atmosphere, and motions introduced, for example, by solar plasma outbursts and by the rotation of the earth. The boundary conditions discussed before, both at the interior and exterior boundaries of the magnetosphere, require consideration when discussing the dynamics, for as Gold[25]

25. Gold, T., Motions in Magnetosphere of the Earth, J. Geophys. Res. 64, 1219 (1959).

has pointed out, on the interior boundary the insulating atmosphere provides a "disconnecting" mechanism between the solid earth and the magnetosphere allowing free exchange of field lines. Indeed, such a mechanism may obviate the question of spin damping raised before.

It is generally thought that the magnetosphere shows a high order of regularity out to some 5 Re (Re = geocentric radii).[26, 27] The large-scale dipolar field order* provides a

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26. Sonett, C. P., D. L. Judge, A. R. Sims, and J. M. Kelso, A Radial Rocket Survey of the Distant Geomagnetic Field, J. Geophys. Res. 65, 55 (1960).
27. Heppner, J. P., N. F. Ness, T. L. Skillman, and C. S. Scearce, Magnetic Field Measurements with the Explorer X Satellite; in press, Proc. Kyoto Conf. on the Earth Storm and Cosmic Rays (1961), NASA TN D-1061.

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setting in which the magnetic energy density exceeds the gas kinetic energy density by an amount sufficient that hydromagnetic turbulence probably does not exist and the Alfven signal velocity can, for many purposes, be assumed isotropic. It is in this region of space that the Van Allen belts exist and that ring current effects may be important. The actual geomagnetic-

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*Large-scale order is not intended to imply the absence of currents, but rather "mixing," turbulence, or large waves.

interplanetary interface (the outer boundary of the exosphere) possibly has a variable distance from the earth, depending on the longitude with respect to the earth-sun line and perhaps, also, upon the state of solar activity. Present indications from space probes are that the magnetosphere may be divisible into two regions having fundamentally different hydromagnetic behavior. These are the magnetosphere proper, characterized by a magnetic pressure much greater than the gas pressure, or $H^2/8\pi$ nkt $\gg 1$ out to perhaps 5 - 7 Re, and what may be termed the magnetopause, where more nearly $H^2/8\pi$ nkt ~ 1; in the magnetopause, the field appears to be subjected at times to shock waves, disorder, and perhaps other species of hydromagnetic activity.[27, 28] (These correspond to high and low β cases of laboratory plasma physics.)

28. Sonett, C. P., E. J. Smith, and A. R. Sims, Rocket Surveys of the Distant Geomagnetic Field, Space Science; ed. H. J. Kallman-Bijl., N. Holland Publ. Co. (1960).

Although a considerable literature now exists on the physics of the magnetosphere, much of this work is yet of a theoretical nature and has little supportive evidence experimentally. It does, however, form the groundwork against which the reduction and analysis of experimental data from satellites can be examined. The magnetosphere demands consideration in the context of a closed volume surrounding the earth so that any solar phenomena propagated earthward must pass through it; it acts

essentially as a transmission medium. These characteristics must be understood in order to develop the relationship between interplanetary phenomena and resultant geophysical effects seen on the surface of the earth.

Ring currents far antedate the discovery of the magnetosphere. They were first proposed by Birkeland and by Stoermer to explain the latitude of the auroral zones. Later, others, including Chapman and Ferraro, invoked the concept of a ring current to explain the apparent symmetry of the main phase decrease of magnetic storms. With the **discovery** of the magnetosphere, it became important to fold into it the hypothesis of a ring current. One of the first to attack this problem was Singer,[29] who proposed that the drift of positive and negative

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29. Singer, F. S., A New Model of Magnetic Storms and Aurorae, Trans. Amer. Geophys. Union 38, 175 (1957).

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particles in the inhomogeneous field of the earth in itself constituted a ring current which existed all the time and depressed the field at the surface below that of normal dipolar value. Following this work of Singer came the discovery by Van Allen of trapped particles at very high energy.[30] Attempts were

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30. For example: Van Allen, J. A., C. E. McIlwain, G. H. Ludwig, Jr., Radiation Observations with Satellite 1958 Epsilon, J. Geophys. Res. 64, 271 (1959).

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then made to fit the Van Allen radiation belts into the ring-current concept. Most of these attempts centered around the idea of drift currents of charged particles in the inhomogeneous field. Dessler and Parker[31] then proposed that diamagnetic effects were

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31. Dessler, A. J. and E. N. Parker, Hydromagnetic Theory of Geomagnetic Storms, J. Geophys. Res. 64, 2239 (1959).

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important. Their model of the ring current placed the center at the peak of the second Van Allen radiation belt at approximately 4 Re. AtAabout the same time, the magnetometer experiment on Explorer VI by Sonett and coworkers[32] showed distinctly that

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32. Sonett, C. P., E. J. Smith, D. L. Judge, and P. J. Coleman, Jr., Current Systems in the Vestigial Geomagnetic Field, Phys. Rev. Lett. 4, 1961 (1960).

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large-scale currents were flowing in the far exosphere of the earth because of the large anomalies which were seen on most days during the six weeks in which the magnetometer was operating. Neither the Pioneer I nor Explorer VI experiments noted large-scale

field deviations at geocentric distances of less than 5 Re,[26, 32] whereas both Lunik I[33] and Explorer X[27] reported a large anomaly

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33. Dolginov, S. Sh. and N. V. Pushkov, Magnetic Field of the Outer Corpuscular Region, Proc. Moscow Cosmic Ray Conf. 3, 30 (1960).

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in the field at $\sim$ 2 Re. (See Fig. 4 for Pioneer I.) The Lunik I and Explorer X experiments suggest the existence of a large ring current in the region between the two Van Allen belts. The regular variations in the field beyond 5 Re noted on the Explorer VI experiment were seen again on Explorer X and seemed to extend out to much greater distances.

The Lunik data is somewhat difficult to interpret because the anomaly is about one half the quieseent field making, for example, any linear drift current theory difficult to apply. Very strong pressure gradients are required to sustain this variation. Possible evidence is afforded by Lunik II plasma data where a steep gradient is observed in this region. An additional difficulty is the fact that the field is depressed everywhere which would seem to violate the need to conserve the field energy (and, therefore, amplitude) over such a large volume, this, in turn, requiring positive excursions. (Such a result is also arrived

at directly by consideration of diamagnetic effects.)[34] The

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34. Dessler, A. J., Private communication.

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reversed gradient offers additional difficulties in any interpretation involving conventional drift current theories. This data is shown in Figure 5 along with Lunik II which, interestingly, does not show the same anomaly.

Explorer X shows a totally different effect. (See Fig. 6.) Here, a negative anomaly is seen from $2.0 \leq Re \lesssim 4$. Attempts to fit this to various trajectories is being made. According to Heppner, et al, trajectory errors cannot account for the anomaly.

The functional form of the Explorer X field (insofar as generally available data indicates) is still nearly dipolar. Careful examination of the data in the region of $1.8 \lesssim Re \lesssim 4$ discloses that a dipolar fit cannot be made, i.e., the fractional difference between the theoretical dipole and the measured values shows a maximum. This would not be expected for a monotonic error in the radial coordinate and thus may be understandable only in terms of a current. It remains to determine as for any current in the magnetosphere just what the time dependence is. Although Explorer VI obtained field values in the inner magnetosphere, the accuracy was limited by the non-linear response of the magnetometer. A 30γ deviation at this distance could easily have

escaped detection, since the magnetometer was approximately logarithmic in response. (See Figure 4.) These data are still being examined.

The deformation of the field first seen on Explorer XI, again on Pioneer V, and much extended on Explorer X is a separate problem. The latter spacecraft indicates a persistent deviation out to 21.5 Re, mostly positive. A small negative deviation was noted at ~ 7.5 Re of a few γ. There was no evidence of any obvious similarity to Explorer VI in field amplitude. The angular rotation of the field, however, is quite similar, the Explorer VI case being more involved because of the complication of the apogee turnaround at ~ 8 Re with attendant changes in geomagnetic attitude of the spacecraft.

Currently, two competing explanations for the far disturbances are the existence of a current system closing axi-symmetrically about the earth in the far field,[35] or a field

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35. Smith, E. J., P. J. Coleman, Jr., D. L. Judge, and C. P. Sonett, Characteristics of the Extraterrestrial Current System: Explorer VI and Pioneer V, J. Geophys. Res.,665, 1858 (1960).

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deformation caused by a solar wind.[36, 37] Analysis is presently

36. Piddington, J. H., Geomagnetic Storm Theory, J. Geophys. Res. 65, 93 (1960).

37. Johnson, F. S., The Gross Character of the Geomagnetic Field in the Solar Wind, J. Geophys. Res. 65, 3049 (1960).

insufficient to decide between these alternatives or whether both are correct. In any event, the deformation or geomagnetic tail implies the existence of a current system defined by $\nabla \times H \neq 0$ so that, in either case, a non-zero curl is indicated in the magnetopause. This is an important result from space probes, for it means that the electrodynamics of the magnetosphere and the magnetopause require a modified dipole.

Analysis of data from spacecraft such as Explorer VI and from Explorer X is complicated by the need to study all six degrees of freedom of the spacecraft before completing the magnetic field analysis. For both these spacecraft much of the data is still being processed.

The storm-time field may be related to the often-seen field anomalies of Explorer VI. Recent analysis of storm data for

the period around August 16, 1959 indicates a generalized D_{st} westward current over possibly a broad region of the magnetosphere.[38]

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38. Smith, E. J., and C. P. Sonett, Satellite Observations of the Distant Field during Magnetic Storms: Explorer VI, in press, Proc. Kyoto Conf. on the Earth Storm and Cosmic Rays, September, 1961)

There appears to be a main phase decrease and recovery at 4 Re which coincides with the surface storm effects. Further, the 4 Re decrease is larger by a factor of 3.6. This provides definite evidence for a general magnetospheric current source for the storm time (D_{st}) field. Antsilevich[39] has recently examined

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39. Antsilevich, M. G., Geomagnetic Field Variations on 9, 10, 24, 25 August, 1-2 September 1959, and 11 March 1960, Geomagnetism and Aeronomy 1, 320 (1961).

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surface magnetograms for the time during which Explorer VI was in flight and finds some correspondence between surface and satellite measurements.

Limited information of a preliminary sort has just become

available from Explorer XII. Cahill[40] reports no evidence of

40. Cahill, L. J., Preliminary Magnetic Results of Explorer XII, Explorer XII Symposium, Goddard Space Flight Center, Greenbelt, Md., January 18, 1962.

magnetospheric currents but finds evidence of a termination at $\sim$ 10 Re. The negative finding is accurate to about 20 γ as this is the limit of digitization of the data. Rotation of the field was not available since the expected dipolar direction as seen by the spacecraft was not available. If the digitization transitions are read, these are probably precise to something like 0.1-1 γ (better than the flux gate magnetometer zero). However, an unknown $\pm$ 20 γ variation could exist and not be detected. If the data passes through two adjacent digitization transitions, the 20 γ separation of levels is resolved, but two new ambiguities totaling 40 γ are introduced. The effect of this upon the angular accuracy can be easily calculated by the reader and depends partially upon the resolution of the field in spacecraft coordinates.

Since the curl of $\vec{H}$ is a tensor whose components are given by $\partial H_i / \partial x_j$, it is clear that definitive study of the currents associated with field distortions requires a

program using earth satellites that have a high degree of sophistication. Single traversals by probes and other limited arrangements will not, in the long sense, provide the components of the curl. The time variance of field perturbations, particularly in the magnetopause, must also be folded into a proper field description. Even with the assumption of ignorable displacement currents, the extreme difficulty of ever obtaining a complete description of $\nabla \times H$ suggests that a microscopic (individual particle) analysis is needed. It is important to recognize that the self-consistent theory required when large deformations of the field are encountered will require extensive study before the magnetospheric field can be specified with completeness. Dessler and Karplus[41] have presented strong arguments for a storm time

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41. Dessler, A. J. and R. Karplus, Some Effects of Diamagnetic Ring Currents on Van Allen Radiation, J. Geophys. Res. 66, 2289 (1961).

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current at about 4 Re. The results of Apel,[42] used by them, show

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42. Apel, J. R., Geomagnetic Field Perturbations due to Trapped Particles, M. S. thesis, Univ. of Maryland, 1961.

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that a diamagnetic pair of currents may produce a decrease at the surface in spite of the lower altitude of the eastward component.

This, together with energy considerations, makes the likelihood of broad, diffuse currents centered perhaps at 3 - 5 Re quite attractive and is consistent with the recent analysis of Explorer VI data.[38]

The rotation of the earth may be important in the balance of forces in the magnetosphere. Such a problem was considered in the corotation of the interplanetary field with the sun by Lüst and Schlüter, though their interest was generated by the question of magnetic spin damping in stars.[9] The same general problem has been treated by Block.[10] In the earth's magnetosphere beyond the distance of synchronous rotation defined by

$$R_0^3 = \frac{GM}{\omega^2} \tag{9}$$

the magnetic field becomes the constraining agent. In short, the equilibrium condition is hydromagnetic (Eq. 1) and is governed by the equation of motion of a rarefied plasma in the presence of pressure (∇p) gradients and gravity. A uniquely magnetic constraint is applicable at distances beyond which these quantities are important.

B. Plasma Experiments

To understand the properties of ring currents which appear to flow in the magnetosphere requires detailed information on the plasma and density gradients, for the flow of currents is governed by the equations of bulk hydromagnetics which contain, in addition to the gravity potential, the pressure gradient as well as body forces.

There are some data available at the present time from satellites on the question of density and density gradients. In Table 1 are listed the principal plasma experiments which have been conducted on space probes and high altitude satellites. The lower altitude Sputniks and Explorer VIII have not been included. Principally, three types of instruments have been used, the U.S.S.R. favoring the ion trap of hemispherical design. Gringauz, et al[43] have provided a description of this equipment. On

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43. Gringauz, K. I., V. V. Bezrukikh, V. D. Ozerov, and R. Ye. Rybchinskiy, Study of the Interplanetary Ionized Gas, High Energy Electrons, and Solar Corpuscular Radiation by Means of Three Electrode Traps for Charged Particles on the Second Soviet Cosmic Rocket, Artificial Earth Satellites, #6 Moscow (1961).

Lunik II, it consisted of a hemispherical N_i screen enclosing

a flat Ni collector which was itself covered by a tungsten photoelectric suppressor grid. There were four traps on Lunik II, and the vehicle performed attitude maneuvers* so that at all times one trap was shielded from the sun, providing a test for photoelectric currents. An important adjunct to the arrangement was the ordering of potentials with respect to the spacecraft body: internal collectors 60 - 90 volts negative; photosuppressor grids 200 volts negative; outer cover screens -10, -5, 0 and +15 volts. Incomplete information is available to this writer on the equipment aboard Lunik I and the Venus probe; the comments of Gringauz, et al indicate at least a qualitative similarity to Lunik II. One difference is that on the Venus probe the maximum positive potential was increased to +25 volts.

There appear to be two primary results within the confines of the magnetosphere. First, a relatively cold plasma (in contrast to the Van Allen radiation) was noted to 2.8×10^4 km though the apparent concentration of $\sim 500 \text{ cm}^{-3}$ began to droop just past 2.1×10^4 km. The density was "hydrostatic" to 2.1×10^4 km. The temperature is estimated from current modulation on the negatively biased traps as having an upper bound of $\sim 5 \times 10^4$ °K. It is important to note that in this interval

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*It is not clear from the available translation whether these were controlled maneuvers or tumbling; either suffices for the photoelectric tests.

electron currents were very small or zero, even on the +15 volt trap.

From 2.8×10^4 to 5×10^4 km negative currents varying from zero to 6×10^{-10} amps were noted on all traps indicating, it would seem, electron bursts of energy ≥ 15 volts.

From 5×10^4 to 7×10^4 km, simultaneous electron currents were seen on all four traps. Gringauz and Rytov[44] have compared

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44. Gringauz, K. I. and S. M. Rytov, On the Relationship between the Magnetic Field Measurements Obtained by Soviet Cosmic Rockets with Charged Particle Traps and those obtained by U.S.A. Explorer VI and Pioneer V, Proc. Acad. Sciences U.S.S.R. 135, 48 (1960).

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these results with the computations of Smith, et al for the magnetometer data of Explorer VI and Pioneer V and find the plasma and field measurements to be consistent for the assumption of a large ring current. It must be remembered that Dessler and Karplus[41] have pointed out that consistency is obtained by postulating a body of electrons not actually seen by Gringauz, et al. As they show, there may be serious problems with trying to reconcile the Explorer VI and Lunik II data. Furthermore, the ambiguity as to whether the Explorer VI quiet time perturbation

was a drawn-out tail or a ringlike current is not resolved. This question is certainly intensified by the Explorer X results.

The results during passage through the second Van Allen belt are particularly puzzling. The latest available data by Rosen and Farley[45] from Explorer VI indicates that the outer belt

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45. Rosen, A. and T. A. Farley, Characteristics of the Van Allen Radiation Zones as Measured by the Scintillation Counter on Explorer VI, J. Geophys. Res. 66, 2013 (1961).

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flux, if electrons, is 2×10^7 cm^{-2} sec^{-1} for 500 KV,* and 2.7×10^9 cm^{-2} sec^{-1} above 200 ev. This would imply that the experiment of Rosen and Farley saw much of the radiation and that the commonly postulated low, i.e., 20 KV, sea of electrons, is non-existent. This is in strong contrast to the deductions of previous observers who estimate fluxes many orders of magnitude higher.

The electron stream results at 5×10^4 to 7×10^4 km are taken by Gringauz, et al to imply a flux of $1 - 2 \times 10^8$ electrons/cm^2 sec with energies above 200 volts, leading them to

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*This is from the relatively bremsstrahlung insensitive organic phosphor detector. The two values quoted are for satellite penetration and non-penetration, respectively.

postulate a third outermost belt.[46] It is of specific interest

46. Gringauz, K. I., V. G. Kurt, V. I. Moroz, and I. S. Shklovsky, Ionized Gas and High Speed Electrons in the Vicinity of the Earth and in Interplanetary Space, Proc. Acad. Sciences, U.S.S.R. 132, 1062 (1960).

to consider the relation of their measurements to those of Sonett and coworkers, for Gringauz and Rytov claim to show a quantitative consistency between their electron stream measurements and the simple, non-diamagnetic ring current model as mentioned above.

The highly diamagnetic ring current, primarily protonic, as proposed by Dessler and Parker[39] and studied by Apel[42] shows a drift maximum at 4 Re, the combination of drift current and diamagnetism providing a general field depression from the surface of the earth to out past 4 Re.* The electron stream of Gringauz, et al leads them to suppose a volume density $\sim 600\ cm^{-3}$ in the region of their observation. Clearly, the general importance of density gradients along with field gradients in establishing the pattern of ring currents points out the need for comprehensive plasma pressure gradient data.

*These results presuppose an ad hoc distribution of volume density and temperature for the plasma.

Explorer X was equipped with a variable, integrally biased Faraday cup with photoelectric suppression.[47] A schematic

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47. Bridge, H. S., C. Dilworth, B. Rossi, and F. Scherb, An Instrument for the Investigation of Interplanetary Plasma, J. Geophys. Res. 65, 3053 (1960).

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diagram of the cup is shown in Fig. 8. The bias gates were discretely variable from 0 to 2300 volts in 8 steps. Preliminary findings from this experiment indicate that from 1.3 Re to 2.9 Re cold plasma was encountered.[48] The vehicle velocity can

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48. Bridge, H. S., C. Dilworth, A. Lazamus, E. F. Lyon, B. Rossi, and F. Scherb, Direct Observation of the Interplanetary Plasma; in press, Proc. Kyoto Conf. on the Earth Storm and Cosmic Rays (1961).

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be estimated to have been about 10^6 cm/sec. at injection. The electrometer current was spin modulated in this interval. From the velocity, then, one estimates a maximum proton energy in this region of space of ~ 1 ev (electrons were not sensed by this probe). Beyond 2.9 Re, no ion current was registered until the vehicle had ascended to 21.5 Re. The results are discussed later,

together with field results. Threshold for this instrument was $\sim 5 \times 10^{6}$ cm^{-2} sec^{-1}. Therefore a, say, 25,000^{o}K proton temperature would indicate a volume density threshold of ~ 10 cm^{-3}.

Explorer XII 's initial apogee was approximately in the sub-solar direction in comparison to Explorer X, where apogee was about midnight. Little data is available yet from this experiment. The plasma probe was a curved plate analyzer for which the operation is differential, rather than in egral as in the case of Bridge, et al. A detailed description of the operation of this general type of equipment is given by Bader.[49] The

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49. Bader, M., On the Problem of Obtaining Thermal Proton Background and Solar Wind Measurements in Space. Rand Symp. on Aerodynamics of the Upper Atmosphere (unpubl.).

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instrument is shown in Fig. 9. What data there is indicates a few, short, occasional bursts of plasma at distances of 6×10^{4} to 8×10^{4} km geocentric. A few minutes of data would be obtained and then perhaps a half hour of quiet. The indicated plasma density varies from 1 to 10 per cm^{3} during these bursts with an energy of 2 to 15 KV. Cold plasma was not seen close

to the earth. However, this cannot be precluded from further data analysis.[50]

50. Bader, M., Private communication.

In summary, the available data from Lunik I, Lunik II, and Explorer X concerning the inner magnetosphere are qualitatively consistent though quantitative Explorer X data for the inner field is not available. Since Explorer X was not equipped to study electrons direct comparison from 4.7 Re to 21.5 Re could not be made. It is curious that the inner magnetospheric cold plasma disappeared at 2.9 Re on Explorer X, even though the sensitivity appears to be higher than Lunik II by a factor of 20.*

Another source of data concerning the thermal plasma density in the magnetosphere is obtained from whistler echoes. The study of time delay echoes of whistler-mode propagation in the magnetosphere has the advantage of inherently including thermal component of the plasma. However, it suffers the disadvantage of obtaining a weighted mean value of plasma density

*This is arrived at from a quoted figure (Explorer X) and a threshold inferred from Gringauz, et al.

along a tube of force.* Although satellites are beset by the problem of electric charge in determining the very low energy component of the plasma, they can, on the other hand, map the field of plasma obtaining the spatial distribution and thereby provide information on pressure gradients.

C. Waves

Though propagation in the magnetosphere is characterized by the many allowed modes of a binary gyrotropic plasma having passbands and stopbands reminiscent of a polyrefringent crystal, there are the important additions that the magnetic field is curved and that finite amplitude waves can exist. It is both convenient and physically important to consider separately the modes which propagate below the local gyro frequency. In particular, the modes which propagate below the ion gyro frequency are, loosely termed, hydromagnetic. It is these modes which appear to characterize many of the interesting properties of the magnetosphere. They are, for example, connected with at least some types of micropulsations,[51] the propagation of geomagnetic storm

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51. Troitskaya, V., Pulsations of the Earth's Electromagnetic Field and Their Connection with Phenomena in the High Atmosphere, J. Geophys. Res. 66, 5 (1961).

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*The mean is weighted to the equatorial plasma density since the velocity is a minimum in this region yielding a maximum in transit time.

transients, and may well be connected with acceleration and dissipation of the Van Allen radiation.[52-56] The modes are

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52. Welch, J. A., Jr., and W. A. Whitacker, Theory of Geomagnetically Trapped Electrons from an Artificial Source, J. Geophys. Res. 64, 909 (1959).
53. Dragt, A. J., Effect of Hydromagnetic Waves on the Lifetime of Van Allen Radiation Protons, J. Geophys. Res. 66, 1641 (1961).
54. Parker, E. N., Geomagnetic Fluctuations and the Form of the Outer Zone of the Van Allen Radiation Belt, J. Geophys. Res. 65, 3117 (1960).
55. Parker, E. N., Effect of Hydromagnetic Waves in a Dipole on the Longitudinal Invariant, J. Geophys. Res. 66, 693 (1961).
56. Davis, Leverett, Jr. and David B. J. Chang, On the Effect of Fluctuations on Trapped Particles, presented at AGU Natl. Meeting, Los Angeles, Dec., 1961.

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chiefly the transverse, or Alfven, mode which propagates two circularly polarized waves in the direction of the field at the phase velocity $v = \frac{H}{\sqrt{4\pi\rho}}$ where ρ is the particle density in gms/cm^3, and a longitudinal mode which propagates across

the field* in a manner somewhat analogous to an acoustic wave for which the velocity is modified by the presence of the magnetic field.** In the magnetosphere proper ρ is a slowly varying function of position, and velocity is regulated primarily by the field. In the ionosphere, decoupling occurs and the propagation becomes more complex.[57]

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57. Francis, W. E. and R. Karplus, Hydromagnetic Waves in the Ionosphere, J. Geophys. Res. 65, 3593 (1960).

The Argus experiment provides what appears to be the first direct evidence of transmission via hydromagnetic modes. Additional evidence has been found from the fine structure analysis

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*Propagation along the field can, of course, take place for an acoustic wave, though for infinitesimal waves, it is decoupled from field effects.

**MacDonald has recently characterized the hydromagnetic modes in terms of a propagating vorticity and divergence of the velocity field associated with the magnetic effects.[58]

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58. MacDonald, G. J. F., Spectrum of Hydromagnetic Waves in the Exosphere, J. Geophys. Res. 666, 639 (1961).

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of the field both for Pioneer I and Explorer VI data.[59, 60]

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59. Sonett, C. P., A. R. Sims, and I. J. Abrams, The Distant Geomagnetic Field, I: Infinitesimal Hydromagnetic Waves, J. Geophys. Res., to be published in April issue.
60. Judge, D. L. and P. J. Coleman, Jr., Observations of Low Frequency Hydromagnetic Waves in the Distant Geomagnetic Field; Explorer VI, in draft.

The geometry of a satellite in a geomagnetic coordinate system allows specification of the various wave modes which are possible. An example of the separation of wave modes in the detection of hydromagnetic phenomena in the magnetosphere has been given for the case of Pioneer I, where a study of the amplitude and phase of the magnetometer signal allowed a partial separation of the transverse Alfven and the compressional or magnetoacoustic modes to be affected. In that experiment, hydromagnetic activity was demonstrated in the region of 3.7 to 7 earth radii in the sunlit hemisphere. Details of the procedure for decoupling modes are given by Sonett, et al.[59] Typical power spectra for amplitude and phase are shown in Figs. 10 and 11. There are, in certain instances, pure magnetoacoustic modes, pure transverse modes, and a third instance shows a coupling of the two modes.

Typical hydromagnetic wave energy densities varied from 10^{-13} to 10^{-12} ergs/cm^{-3} from 0 - 1 cps. The finite line widths found provide a measure of broadening, possibly due to positive ion Landau damping. In general, these spectra suggest excitation of the far magnetosphere, perhaps at the boundary. On the assumption that the available sample was representative of the magnetospheric volume to $\sim$ 7 Re, the hydromagnetic energy appeared to be of order 10^{18} ergs over 1 cps. In contrast to magnetic storm activity, this is trivial over short time spans, and its importance must be assessed over periods of months.

Data from Explorer VI shows that combined magnetic and particle effects attributable to the occurrence of magneto-acoustic waves with attendant adiabatic particle acceleration can occur at certain times. An example of an out-of-phase correlation between magnetometer and scintillation counter on Explorer VI is given by Farley and Rosen.[61] This type of disturbance, as well as quiet time field oscillations, have been

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61. Farley, T. A. and A. Rosen, Charged Particle Variations in the Outer Van Allen Zone during a Geomagnetic Storm, J. Geophys. Res. 65, 3494 (1960).

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studied in detail by Judge and Coleman.[60] Coleman[62] has made a

62. Coleman, P. J., Jr., The Effects of Betation Accelerations upon the Intensity and Energy Spectrum of Magnetically Trapped Particles, J. Geophys. Res. 66, 1351 (1961).

relativistically correct calculation of the spectral changes to be expected in the Van Allen belts, assuming a power law, when the field is subject to adiabatic compressional variations. Application of these to the Explorer VI data yields an integral spectrum with exponent -1. The waves used were observed to have periods of 100 and 500 seconds with amplitudes as high as 30 γ in a base field of $\sim$ 100 γ. The presence of Alfven waves was also indicated, since the sun scanner showed angular changes of $\sim 15^{\circ}$. A most interesting additional effect was the sporadic presence of damped trains with decay $\sim$ 500 seconds. These are consistent with Suguira's[63] observations in

63. Suguira, M., Evidence of Low Frequency Hydromagnetic Waves in the Exosphere, J. Geophys. Res. 66, 4087 (1961).

polar regions of the circularly polarized transverse mode. The lines of force on which Judge and Coleman made their studies were those which end in or near the auroral zones.

D. The Magnetopause

Until recently, it was held that the geomagnetic field extended to some 5 Re (geocentric radii), and was terminated on the solar side by the pressure of a solar wind. Parker[64] has

64. Parker, E. N., Interaction of the Solar Wind with the Geomagnetic Field, Phys. Fluids 1, 171 (1958).

pointed out that during storms the wind pressure might increase from a quiet time value of perhaps 10^{-8} dynes/cm^2 to perhaps 10^{-6} dynes/cm^2, thus collapsing the field on the solar side to some 2 - 3 Re. These concepts were an outgrowth of the Chapman-Ferraro theory of the earth storm published in 1931.[65-67] Dungey

65. Chapman, S. and V. C. H. Ferraro, A New Theory of Magnetic Storms, Terr. Mag. and Atm. Elect. 36, 77 and 171 (1931).
66. Ibid., 38, 79 (1933).
67. Ibid., 45, 245 (1940).

later elaborated on some possible results of a wind interacting with the geomagnetic field with emphasis upon quiet times.[68]

68. Dungey, J. W., Cosmical Electrodynamics, Chapt. 8, Camb. Univ. Press (1958).

The details of any interaction model between a wind and the field generally follow Chapman and Ferraro. The results from the major storm sequence observed by Pioneer V indicate that magnetic pressures of 10^{-8} dynes/cm^2 can accompany a storm plasma.[69] This means that field momentum may be important in

69. Coleman, P. J., Jr., C. P. Sonett, and Leverett Davis, Jr., On the Interplanetary Magnetic Storm: Pioneer V, J. Geophys. Res. 66, 2043 (1961).

this problem and the impingement of a field-free plasma upon a plasma-free geomagnetic field as assumed by Chapman and Ferraro and others may bear reexamination. Nevertheless, some form of cavity satisfying both Maxwell and mechanical boundary conditions seems to follow from the limited analyses which have so far been made.

The model of the magnetopause involving a mechanically deformed tail should be dependent upon the status of the solar wind on any particular day. The findings of Pioneer V would indicate that, at the time of flight, about 50 per cent of the time the interplanetary field was in a quiescent condition.[70]

70. Coleman, P. J., Jr., Leverett Davis, Jr. and C. P. Sonett, The Steady Component of the Interplanetary Magnetic Field, Phys. Rev. Lett., 5, 43 (1960).

Hultqvist[71] indicates that perhaps 25-30 per cent of the time

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71. Hultqvist, Private communication.

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the auroral magnetic field does not display severe variations. On this basis, it seems reasonable to suggest that the orientation of a geomagnetic tail would be determined by the wind velocity, vectorially modified by the aberration introduced by the earth's motion. This assumes that any stationary plasma with velocity equal to that of the earth's orbital speed does not coexist with the wind.[72] Otherwise, the pressure vectors of the two plasmas

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72. Biermann, L., Solar Corpuscular Radiation and the Interplanetary Gas, The Observatory 77, 109 (1957).

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would define the tail direction which would then not necessarily be aligned along the apparent (aberrated) wind velocity vector. In any event, the tail should swing through directions bounded, at most, by dusk and the anti-solar direction, the former obtaining in the event of an extremely weak wind velocity. There is presently little experimental data available to use in exploring this question though the data of Explorer X does appear to satisfy the model of a swept-out tail.

The data of Explorer X[27, 48] in its traverse of the distant magnetosphere or magnetopause is particularly interesting. Generally, any plasma to 21.5 Re was below threshold which was 4 times lower than Lunik II for ions. However, electrons could not be sensed so a confirmation of the Lunik II electron stream results could not be made. The sudden appearance of disordered field and sporadic plasma at 21.5 Re argues for a geomagnetic termination. This is shown in <u>Fig. 12</u> where for $\lesssim$ 21.5 Re the field is nearly radial from the sun* and suddenly displays rapid variations as large as $\pm \pi/2$ and the plasma is peaked well above zero energy. A peculiarity of the data is the out-of-phase correlation of plasma and field much as was noted on Explorer VI during a magnetic storm. It is stated by the experimenters that plasma streams were seen emanating from the general vicinity of the sun and only when field values were depressed. Reference to <u>Fig. 12</u> shows the sudden onset of disorder but also shows a tendency for the field direction to be along the spacecraft spin axis ($\alpha = 0^\circ$) and at 45° to the sun** in contrast

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*The normal geomagnetic field direction may be ambiguously close to the solar direction at the time of these measurements.

**The angles used are the same as previously discussed in the various papers on Explorer VI, being the spin axis-field angle (α) and the azimuth in the spacecraft equator (ψ).

to normal to the spin axis and in the anti-solar direction prior to the appearance of the instabilities. Rossi[73] has additionally

73. Rossi, B., Discussion at Kyoto Conf. on the Earth Storm and Cosmic Rays (1961).

pointed out that the "turbulence" would indicate equipartition of gas kinetic and magnetic energy densities. Typically, a region of $\sim 10^{11}$ cm scale and of density $\sim 10\ cm^{-3}$ would be followed by another cell where $n_p \sim 0.2\ cm^{-3}$ having the same scale size. The ordered plasma energy density $\sim 8 \times 10^{-9}$ $ergs/cm^3$ when the magnetic energy density was $\sim 4 \times 10^{-10}$ $ergs/cm^3$. From this, it appears that the thermal or disordered gas kinetic energy density was $\sim 4 \times 10^{-10}$ $ergs/cm^3$, indicating for $n_p \sim 10\ cm^{-3}$ a particle thermal energy of ~ 25 ev or some $2 - 3 \times 10^5\ {}^oK$ corresponding* more to, say, a coronal than chromospheric temperature.

A striking phenomena noted was a sudden commencement while in this region (Fig. 13). The field magnitude doubled and the relativity flat plasma spectrum peaked in the 2300-volt channel. The field direction reversed in the sense that the angle, α, went from $\sim 30^o$ to 120^o and returned. This latter

*Assuming protons.

event, however, preceded the sudden commencement by about 1/4 hour. The richness of these phenomena preclude any detailed interpretation at the time of this writing. If the field increase were assumed shocklike then its thickness (assuming not too oblique a passage and 300 km/sec) seems to indicate a preponderance of high energy gas, for it took about 10 minutes to rise, indicating a breadth of $\sim 2 \times 10^5$ km. (In a 10 γ field, the gyro radius of protons would correspond to an energy of $\sim 10^5$ ev.) It is difficult to accept that this is indeed a collisionless shock, for there is no substantiating evidence that particles of such high energy carry the bulk of the plasma momentum. Further, the character of the disturbance shown in Fig. 13 is not that of such a shock, since the downstream field stays high.

E. The Geomagnetic Boundary

Beard,[74] Spreiter,[75] and others[76-79] have examined the

74. Beard, D. B., The Interaction of the Terrestrial Magnetic Field with the Solar Corpuscular Radiation, J. Geophys. Res. 65, 3559 (1960).
75. Spreiter, J. R., and A. Y. Alksne, On the Effect of a Ring Current on the Terminal Shape of the Geomagnetic Field, J. Geophys. Res., in press.
76. Midgeley, J. E. and Leverett Davis, Jr., Computation of the Bounding Surface of a Dipole Field in a Plasma by a Moment Technique, AGU Natl. Meeting, Los Angeles (1961).
77. Dungey, J. W., The Steady State of the Chapman-Ferraro Problem in Two Dimensions, J. Geophys. Res. 66, 1043 (1961).
78. Ferraro, V. C. A., An Approximate Method of Estimating the Size and Shape of the Stationary Hollow Carved out in a Neutral Ionized Stream of Corpuscular Impinging on the Geomagnetic Field, J. Geophys. Res. 65, 3951 (1960).
79. Hurley, James, Interaction between the Solar Wind and the Geomagnetic Field, N.Y.U. College of Engr. Rpt. (1961).

form of the boundary with the assumption of a field-free zero temperature plasma incident upon a plasma-free magnetosphere. This type of model displays a complex sheet of currents over the

boundary having an approximate resemblance to an eastward flowing current in the region of the equatorial sub-solar point. Non-equatorially, the currents deviate from this simple picture. In general, they close about the null lines which represent the axis of the geomagnetic dipole deformed somewhat towards the solar direction. The closure of the boundary currents on the night side becomes somewhat more difficult to discuss. Johnson's[37] topology shows lines from the sunlit hemisphere folding over to the dark side. Indeed, the dipolar axis closes on itself, coupling the polar regions so as to supply a winter polar ionosphere. This field, however, does not provide the auroral entrability of the models which provide O-type nulls facing the solar wind.

The dynamics of the impact phenomena of a solar wind having a thermal energy density 0.1 that of its ordered energy density, as indicated by Explorer X, upon the geomagnetic field is presently an intractable mathematical problem. Numerous suggestions have been made concerning the generation of surface waves, torsional waves, shock waves, hydromagnetic analogs of Rayleigh-Taylor instabilities and other effects such as particle acceleration. In addition to Explorer X, there is available data of two flights, Pioneers I and V, showing intense hydromagnetic activity out to some 14 Re on the solar side of the field.[28]

Both a geomagnetic termination (Fig. 14) and the appearance of shocklike disturbances (Fig. 15) suggest a complex interaction taking place. One result of the Pioneer I data is the difficulty of making a momentum balance across the boundary unless the bulk of the incident wind momentum presumed present is convected into the field by these waves.[80] These hyperwaves have front-rear

80. Sonett, C. P., Coupling of the Solar Wind and the Exosphere, Phys. Lett. 5, 46 (1960).

slope asymmetries with oscillating rear slope structures suggestive of the collisionless hydromagnetic pulses studied theoretically by a number of investigators.[81] The frequent association of these

81. See, for example, Gardner, C. S., H. Goertzerl, H. Grad, C. S. Morawetz, M. H. Rose, and H. Rubin, Hydromagnetic Shock Waves in High Temperature Plasmas in Progress in Nuclear Energy, Ser. XI, Vol. 1, p. 232, Pergamon Press (1958).

pulses with field zeros on their upstream sides suggests the

penetration of the field by a rain of hypersonic plasma bubbles.[82]

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82. Sonett, C. P., Hyperwaves, Shock-like Phenomena in the Outer Exosphere, Proc. Kyoto Conf. on the Earth Storm and Cosmic Rays (1961).

Particle acceleration is strongly suggested by theoretical studies of collisionless pulses and is consistent with the magnetic observations. Strong support for electron acceleration* in this region (the magnetopause) comes from Pioneer IV where order of magnitude fluctuations in electron count rate were observed in essentially the same region of the magnetopause as for Pioneer I.[83]

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83. Van Allen, J. A. and L. A. Frank, Radiation Measurements to 658,300 km with Pioneer IV, Nature 184, 219 (1960).

(See Fig. 16)) The bearing of this upon the local acceleration hypothesis for the Van Allen radiation is apparent. The implication of this shock exitation mechanism would seem to encompass other situations where magnetoionic gas clouds collide, a process of reasonable probability in the galaxy at large. The energy

*A reversed role implying electron acceleration has been implied by Gardner, et al.

density of the field of hyperwaves seen on Pioneer I is also of correct value to be consistent with the recent theory of Axford and Hines[84] which requires a convection of energy from the solar

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84. Axford, W. I. and C. O. Hines, A Unifying Theory of High Latitude Geophysical Phenomena and Geomagnetic Storms, Can. J. Physics 39, 1433 (1961).

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to anti-solar regions of the magnetosphere to account for a number of interesting geophysical phenomena.

Mention should be made here of the terminal data of Explorer XII as reported by Cahill[40] where large angular reversals in the region of 8 - 10 Re have been observed without accompanying magnitude charges over distances of $\sim$ 100 km. It is tempting to think of these as X-type nulls though the data analysis is still in a formative stage and strong conclusions are perhaps not yet warranted.

IV. THE INTERPLANETARY CAVITY

A. Introduction

A sufficient and necessary model of the interplanetary cavity must explain certain cosmic ray phenomena seen on earth, such as the modulation of the galactic cosmic radiation, Forbush decreases, and the diurnal, 27-day, and 11-year cycles as well as the propagation of solar cosmic rays and other debris of solar flare explosions. Phenomena other than cosmic ray variations, for example, long-term changes in the character of micropulsations, the magnetic moment of ring currents, and the density of plasma in the magnetosphere may turn out to be related to solar activity. In this vein, the transparency of the medium between sun and earth, as well as its physical effects, may be important, though it is perhaps too early to dwell on this.

There is little direct rocket data in this region. Most of the model structure has been laboriously constructed from earth surface studies of cosmic ray variations and solar-terrestrial magnetic storm phenomena. Some additional information has come from investigations of comet tail-plasma interactions and from investigations of the properties of the zodiacal light. The results of these studies are subject to some controversy; factors of five to ten difference in plasma density appear in the literature, though there appears to be substantial evidence of an

interplanetary medium.

Two primary problems have been identified in the physics of this region. The first is the quiet time behavior, composed of the extension of the solar corona, the breakdown of corotation, the coupling of the interplanetary and galactic fields, and hydrodynamics of the gas flow. The second outstanding problem today is that of solar-terrestrial relations. It may seem surprising that this latter subject is over one hundred years old, since it was first established in 1855 by Carrington and Hodgson that a conspicuous brightening on a small region of the sun was followed almost immediately ($\sim$ 8 minutes) by a minor geomagnetic disturbance and about one day later by a very severe magnetic storm. This fortuitous observation might well be considered as the beginning of the study of the field of solar-geophysical phenomena, for it was with this observation that it was first recognized that there was either a flow of corporeal matter, electromagnetic energy, or a combination of these from the sun to the earth across the intervening stretches of space. From that time on, developments in this field were slow because of the lack of modern observational techniques. However, even as long ago as 1896, Birkeland proposed that geomagnetic storms were the result of particle streams emitted from the sun. It was he and Störmer as well as others who proposed that the aurora was in some

way connected with the flow of matter from the sun and that a large-scale ring current, i.e., a current situated axisymmetrically about the earth in the form of a torus, having a radius various hypothesized between 5 to 100 earth radii in distance, was responsible for the fact that auroral particles were seen to enter the earth's atmosphere maximally at some 67° geomagnetic latitude rather than at the poles, where dipolar entrance is most allowed. The combination of the earth's dipole and this ring current then provided a path such that the threshold for entrance of charged particles would occur at 67° magnetic.

Reference will be made in this section to data taken directly in interplanetary space by the use of space probes, with some discussion of comets because of their history in the development of the solar wind hypothesis. The extent of theoretical study is large, and it is not intended to cover this area in any detail.

B. Models

The general magnetic field on the sun as observed by Babcock is thought to be distended somewhat by the outward evaporative flow of gas from the solar surface, modified at times by explosive outbursts. The configuration of this field and its connection with the solar corona has not been established. The

extent of the distension of the solar magnetic field into space may be governed by the flow of plasma outward as well as by the magnetic and particulate conditions in interplanetary space itself. Observations by Hewish have indicated that the solar field appears to have a radial component to distances of some 50 solar radii from the sun, this being obtained from the polarization of radio signals during occultations of the crab nebula behind the solar corona.

According to various authors, notably Biermann[72] and Parker,[77] a solar plasma wind during solar quiet exists, and the streaming plasma distends the solar field so that it is propagated outward in the plane of the ecliptic to distances of perhaps 1.5 AU. At this distance, the anisotropic velocity distribution in the plasma is such that the transverse velocity components have an energy density comparable to the distended magnetic field and the field breaks up into a kind of turbulent pattern forming a disordered halo. It is this halo of disordered field which is supposed to move in and out with the solar cycle and to be responsible, at least in part, for the 11-year cycle of flux variations in the galactic component in cosmic rays.[85]

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85. Meyer, P., E. N. Parker, and J. A. Simpson, Solar Cosmic Rays of Feb. 1956 and Their Propagation through Interplanetary Space, Phys. Rev. 104, 768 (1956).

Other models of the interplanetary magnetic field have been postulated from time to time, including the usual tacit assumption that the field is essentially zero, this latter model requiring the interstellar magnetic field to have been swept aside by a solar wind.[86] Clouds of plasma containing disordered fields moving

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86. Davis, Jr., Leverett, Interplanetary Magnetic Fields and Cosmic Rays, Phys. Rev. Lett. 100, 1440 (1955).

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in interplanetary space have also been considered as another source of gas and field by Cocconi, et al.[87] Elliot[8] has proposed, on

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87. Cocconi, G., T. Gold, K. Greisen, S. Hayakawa, and P. Morrison, IUPAP Cosmic Ray Conf. Verona (1957).

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the basis of cosmic ray studies, a dipolar interplanetary field of 3 to 8 x 10^{-5} gauss at earth generated, perhaps, by ringlike currents flowing in the solar corona. This model, which necessarily does violence to a steady solar wind, seems to fit much of the cosmic ray data. To be sure, it is entirely heuristic from the standpoint of interplanetary hydromagnetics. Nevertheless, it is in accord with some of the data presently available.

The solar wind hypothesis which was first proposed as a quiet time phenomena owes its development primarily to the study of the motion of comet tails, which is discussed in a later section. Today, in addition to the school of thought which holds that a quiet time solar wind exists, others suggest, at most, a slow and perhaps steady outflow of gas from the sun, moving at some few kilometers per second.[88*] Although one might be tempted

88. Chamberlain, J. W., Interplanetary Gas III, A Hydrodynamic Model of the Corona, Ap. J. 133, 675 (1960).

to reconcile the Parker-Biermann hypersonic model of the quiet time solar wind with the slow moving case, the physical requirements upon which these two cases are developed are somewhat different. MacDonald[89] has made the suggestion that the outflow of gas from

89. MacDonald, G. J. F., Private communication.

the sun is controlled, not by hydrodynamic flow due to expansion of the solar corona, which would apply to either the Parker-Biermann

*Some models, for example, Elliot's, do not discuss a wind. By inference it must be small; otherwise, the field would disrupt.

or Chamberlain models, but rather to the propagation of hydromagnetic waves which in turn slowly convect plasma outward. The present state of plasma observations are not in complete agreement with the Parker-Biermann solar wind, but are consistent, at least qualitatively, with Chamberlain's study.

Although the magnetometer experiment of Sonett and coworkers on Pioneer V did not provide a unique and unambiguous resolution of the properties of the interplanetary field, the evidence of this experiment is in possible conflict with a hypersonic quiet time solar plasma wind. Russian plasma probe data taken in interplanetary space seems to support models of interplanetary dynamics developed by Chamberlain, Alfven, Block, and others,[90] forming a generally consistent pattern not showing

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90. Alfven, H., The Sun's General Magnetic Field, Tellus 8, 1 (1956).

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gross inconsistency with the magnetometer results.

Consideration of a solar wind, in particular the resultant radiality of any magnetic field, are implied by the energy density of a wind of protons of velocity $\sim 3 \times 10^7$ cm/sec and density ~ 30 cm^{-3} ($\sim 10^{-9}$ $ergs/cm^3$). Thus, any reasonable interplanetary field ($H \sim 2 \times 10^{-5}$ gauss) at 1 AU should be

swept out. Such a model also provides a halo of disordered field at ~ 1.5 AU or more, depending upon exactly where the thermal energy density in the plasma becomes comparable with the magnetic energy density, and is designed to account for the 11-year cycle in the galactic cosmic ray low energy cut-off. There are, however, features of this hypersonic flow which are uncomfortable. In particular, Davis[91] has pointed out that an outward transport of

91. Davis, Jr., Leverett, Private communication.

field from the sun should provide regions of opposed polarity. In the simplest instance of a uniform sweeping out of a large-scale solar field, a null plane should exist congruent with the plane of symmetry of gas flow. Propagation of a "spotty" solar field should still provide null regions. Such regions should tend to collapse because of body forces and lead to a disordering of field and feeding of field energy into the plasma. Such processes have been studied by Parker.[92] A possible example is given by

92. Parker, E. N., Sweet's Mechanism for Merging Magnetic Fields in Conducting Fluids, J. Geophys. Res. 62, 509 (1957).

Sonett, et al[93] during the observation of a magnetic storm-flare

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93. Sonett, C. P., Leverett Davis, Jr., and P. J. Coleman, Jr., Some Aspects of the Internal Structure of a Solar Flare Plasma Cloud, Proc. Kyoto Conf. on the Earth Storm and Cosmic Rays (1961).

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sequence observed on Pioneer V.

It seems reasonable, based on all evidence, to suppose that an outward convection of coronal gas takes place during quiet times. The conflict between the models of Parker and of Chamberlain is intensified by the need of an ad hoc coronal plasma accelerator for the former case,* whereas the velocities required by the Chamberlain are much more modest (few km/sec). The dynamical consequences of which model is correct are, to be sure, far reaching; a limitation of the latter model is its purely hydrodynamic basis, whereas for such a case it seems reasonable to suppose comparable field and plasma energy densities, thereby demanding a hydromagnetic process.

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*Schlüter has suggested that plasma clouds could be accelerated outward in the solar field by the reaction between cloud diamagnetism and the field gradient.

Measurements of electron density in the corona, the zodiacal light, and observation of the scattered Frauhofer spectrum in the zodiacal light have yielded values of which the most current is $\sim 10^2$ cm^{-3}. The assumption of charge neutrality would then imply an equal density of protons. (The question of the contribution of ions of $Z > 1$ has not been explored in detail. A reasonable assumption is that the interplanetary plasma displays the coronal abundances during solar minimum and tends to solar atmospheric abundances during solar maximum as the result of debris accumulated from flare activity.) The detailed balance between plasma and non-ionized hydrogen has been studied by Brandt,[94] who considers recombination, collisional and

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94. Brandt, J. C., Interplanetary Gas. IV: Neutral Hydrogen in a Model Solar Corona, Ap. J. 133, 688 (1961).

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photoionization and diffusion resulting from charge exchange. He finds a density of a few tenths particle per cm^3. His examination of the balance of ionization and recombination provides a means of studying the plasma density by optical examination of L_α resonance radiation.

C. Comet Observations

An indirect approach to the problem of the interplanetary gas is afforded by the work of Biermann[95] and his group. Briefly,

95. For example: Biermann, L. R. Lüst, and E. Trafftz, Comet Tails and Solar Corpuscular Radiation at Times of Small Solar Activity -- Unpublished.

the photoionization rate of cometary nuclei is too low to account for some rapid changes observed optically. For example, the photocrossection for CO is $\sim 1.5 \times 10^{-17}$ cm^2 between 400 and 700 Å. From this, they estimate a 60-day ionization time scale using Johnson's[96] estimate of the solar flux in this wave length

96. Johnson, F. S., Solar Radiation, Chapt. 4 in Satellite Environment Handbook, ed. Johnson, F. S., Stanford Univ. Press (1961).

interval. It is postulated by Biermann and coworkers that charge exchange principally between CO, N_2, and incident protons is much more likely ($\sim 10^{-15}$ cm^2). They estimate that a subsequent exchange of momentum between the resultant cometary ions and the incident electron stream, which he suggests must accompany the incident protons, produces the observed accelerations in comet tails of Type I.* These accelerations, at times, reach 10^2 to 10^3

*Type I comet tails are ionized according to the classification of Bredichin whereas Types II and III are un-ionized CN, C_2, and/or dust.

times solar gravity, a value far too large to be accounted for by radiation pressure alone. Schlüter[97] has suggested that if the

97. Quoted by Biermann, L., Physical Processes in Comet Tails and Their Relation to Solar Activity, Soc. Royale des. Sci. de Liege 13, 291 (1953).

corpuscular radiation carried with it entrained fields, these would provide an additional mechanism for momentum exchange between convected matter and the comet tail. In summary, the study of comet tails has shown that interactions other than radiation pressure must be invoked between plasma injected into the interplanetary medium and certain types of comet tails. Many of the details, in particular, charge exchange reactions which excite radiation in the vacuum ultra-violet (unstudied, to date, because of optical inaccessibility) as well as the contribution of field-plasma interactions to the total momentum balance remain unanswered and would reduce the upper bound on interplanetary gas momentum obtained by these means to values nearer those obtained by plasma probes.

The variation in plasma flow outward from the sun is usually treated two-dimensionally, yet the symmetry of the flow might well be expected to be non-spherical. Some evidence for a heliocentric latitude dependence is suggested by studies of

Beyer[98] which show a marked dependence of brightness of Comet

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98. Beyer, M., Brightness of Comets and Solar Activity, Soc. Royale des Sci. de Liege 13, 276 (1953).

1948a over 50° latitude. For this comet, a variation of 3 magnitudes was noted after correction for both distance from earth and sun. If the visual brightness is proportional to, say, the incident momentum of gas and field impinging on the comet, this represents a factor of 15 in activity.

Rhea Lust[99] has examined comet tails during times of low

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99. Lüst, R., Activity of Comet Tails in Periods of Geomagnetic Calmness, Zeit. f. Astrophysik.

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solar activity and geomagnetic calm. She finds cases where small bursts of activity correlate with cometary brightness increases and correlate best for an assumed transit velocity of 350 km/sec. Finally, a conclusion of Biermann from comet observations is that any stationary interplanetary gas would be expected to interact with a solar wind in a manner analogous to that which seems to exist for comet tails. It might be expected that, in this latter case, the hydrogen-proton charge exchange

cross-section being almost inversely proportional to velocity over 0.2 to 20 KV and $\sim 10^{15}$ cm^2 at 5 KV, any static gas would be rapidly removed.[72] The general conclusion from these comet studies supports the idea of a steady outward flow of interplanetary plasma from the sun during quiet times having a flux of $\sim 10^9$ cm^{-2} sec^{-1} corresponding to a volume density of ~ 30 cm^{-3}.

D. Magnetometer Data

So far, magnetometer flights have been made into the interplanetary cavity by a number of vehicles. These include Pioneer V, Luniks I and II, and the Russian Venus probe. In the Russian flights,[100] the equipment threshold quoted was

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100. Dolginov, S. Sh., E. G. Eroshenko, L. N. Zhuzgov, N. V. Pushkov, L. O. Tyurmina, Measuring the Magnetic Fields of the Earth and Moon by Means of Sputnik III and Space Rockets I and II, Academy of Sciences, Moscow, USSR; in Space Science, ed. Kallman-Bijl., N. Holland Publ. Co. (1960). p. 863.

$\sim 50\ \gamma$ and thus possibly of limited use in discussing the quiescent interplanetary field or, at least, so present data from Pioneer V suggests.

Pioneer V was in operation for some 60 days, moved radially toward the sun about 0.1 AU and traveled some 1.25 x 10^8 km

in orbit during its active life as is shown in Fig. 17. The sun was in a declining state of activity with respect to the 11-year cycle, yet displayed many flares. The data of this experiment[70] indicate that perhaps 50 per cent of the samples taken were representative of a quiet field and that the remaining time was occupied by disturbed conditions. It seems reasonable, then, to infer that two fundamentally different types of data were obtained by the spacecraft. It is important to point out, also, that the magnetometer makes a two-dimensional cut in the field and that this cut is oriented in a fixed direction with respect to the stars. Specifically, the spin axis lay nearly in the ecliptic. Consider a coordinate system with origin in the sun and having a basis set ($\vec{r}, \vec{\theta}, \vec{z}$) which is cylindrical, $\vec{r}$ being the unit vector positive outward from the sun, $\vec{\theta}$ positive in the clockwise direction looking down on the ecliptic, and $\vec{z}$ positive upward. Then field components H_r and H_θ should, if $\vec{H}$ is time invariant, show a semi-annual* periodicity, the two components having a $\pi/2$ phase difference. H_z is time invariant, since it was always oontained in the plane of the spacecraft equator. Thus, the data of the experiment was representable by

$$H_\perp = \left\{ |H_z|^2 + \left[|H_r| \cos \omega t \right]^2 + \left[|H_\theta| \sin \omega t \right]^2 \right\}^{1/2}$$

*"Semi-annual" is defined as one-half the spacecraft year, which was 311 days.

where $H_{\perp}$ is the measured component in the plane of the spacecraft equator. The orientation of the spin axis was such that any appreciable component, H_r, in the quiescent field should have been detected during the 60 days as a sinusoidal variation of the steady field. The same argument applies to H_θ, though here the experimental geometry was such that if a combination of H_r and H_θ existed in the plane of the ecliptic and was spiralled such as to be nearly normal to $\vec{r}$, a sinusoid having insufficient amplitude to have been detected might have resulted. The most reasonable deduction is that the field had a large component, H_φ. Then one is faced with an inconsistency with a quiet time solar wind, for a wind of the energy density suggested by Biermann and by Parker should transport outward any solar field so that the net field would have only $\vec{r}$ and $\vec{\theta}$ components, the relative components depending upon the wind velocity.

What is now left are the alternatives of a field spiralled nearly 90^{o} or the abandonment of a quiet time wind of appreciable energy density. It is important to point out that a field spiralled by such a large angle implies wind velocities so low as to void the basic premise of a hypersonic velocity, anyway.

During disturbed time, the interplanetary field displayed rapid rises in intensity. Indeed, on three occasions (Fig. 18)the

geomagnetic field showed synchronous disturbances larger by a factor of about 3. The most noteworthy of the numerous disturbances studied has been reported by Coleman, Sonett, and Davis.[69] On this occasion, the maximum field[69] was at least 50 γ . A higher value, between telemetry transmissions, was possible. Further, the value measured was of $\left[H_\theta^2 + H_\gamma^2\right]^{1/2}$ the spacecraft spin orientation being in the solar direction at the time. So a 50-100% larger actual field was possible. From these data one can conclude that a curved beam model is tentable for the fortuitous occurrence of solar cosmic rays which were emitted from the sun during this flare sequence.

Finally, the importance of electric fields in the galactic (Forbush) modulation seems to require investigation. Clearly, the motional electric fields estimated to be some 5×10^{-9} volts/cm for the events of Pioneer V, can be alternatively considered from the standpoint of a moving magnetic scatterer. However, this leaves open the importance of time dependent fields in the plasma cloud frame of reference, due to field annihilation, a point which cannot presently be explored in an empirical manner.

There is evidence of fine structure in the interplanetary field which consists of periods of quiet, steady field alternating with what appear to be periodic types of fluctuations. These

are presently under investigation. Of particular interest is a null in the field noted in conjunction with the flare sequence of March 13 - April 1. At this time, the field generally was $\geq 10\gamma$ with wavelike variations. On April 1, a decrease to magnetometer threshold $(\sim 0.5\gamma)$ was noted, lasting for several minutes. Arguments have been given by Sonett, Davis, and Coleman[93] showing how this structure appears to show consistency with a null-surface on the axis of symmetry of the plasma which must have been emitted with the large fields noted in space. Models of a solar flare gas cloud having regions of opposed field within the core have particular correspondence to this observation.

We now turn to the Russian magnetometer data. Information is tabulated in Table II. Data and experimental technique is sparse from these experiments. An upper bound of 50 γ has been established for the lunar field from Lunik II. Neugebauer has pointed out that since the impact was on the solar side of the moon, a solar wind might have collapsed the field to where the last measurement prior to impact would have been exterior to the boundary. Evidence from the far atmosphere of earth indicates that the compression might be more complex than describable by a simple elastic process, leaving this question somewhat open. In any event, the results of Pioneer V indicate the need for magnetometers having a threshold far less than 50 γ for quiescent

field measurements.

Mustel[101] has provided some data on the Russian Venus

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101. Mustel, E. R., U.S.S.R. Report to Commission 16 (Magneto-hydrodynamics) IAU General Assembly, Berkeley (Aug., 1961).

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probe. Here the instruments were "variometers"; design data was not provided. The sensitivity was quoted as 2 γ with range of 50 γ. During the flight of the Venus probe, on February 12 a 4 γ "bump" in the field was noted with a period of 3-5 minutes. Mustel implies that this was a wave, since no associated Forbush decrease was noted. Further information is not available to this author. Lastly, regarding waves, there is a large body of data from Pioneer V showing field variations in the range of minutes. This material is still being processed and detailed results are pending.

E. Cosmic Rays

We discuss here some of the observational cosmic ray data from Pioneer V. The three cosmic ray instruments and their characteristics are listed in Table III. The proportional counter telescope of Fan, et al[102] was of 2 π geometry. The concentric

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102. See, for example, Fan, C. Y., P. Meyer, and J. A. Simpson, Trapped and Cosmic Ray Measurements from Explorer VI, Space Res., ed. H. K. Kallmann-Bizl., N. Holland Publ. Co., Amsterdam, pp. 951-960.

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construction allowed single-triple coincidence events to be registered, the singles corresponding to protons of $E \geq 17$ Mev and to electron and bremsstrahlung photons. The usual steep energy spectra for solar cosmic rays made demonstration of high energy electrons concurrent with the cosmic ray outburst difficult to detect although it was originally suspected by Fan, et al that relativistic electrons were noted in the storm of March 31 - April 1.[103]

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103. Fan, C. Y., Peter Meyer, and J. A. Simpson, The Rapid Reduction of Cosmic Radiation Intensity Measured in Interplanetary Space, Phys. Rev. Lett. 5, 43 (1960).

The simultaneity of the cosmic ray and magnetometer data from Pioneer V provide insight into the play of phenomena in space. We consider, here, the flare sequence of March 30 - April 1 for which the magnetometer data was discussed earlier. Fig. 19 displays the simultaneity of Forbush decrease given by the initial decline in the steady galactic count rate shown by the triples plot and the enhanced field (both indicating the arrival of plasma at the spacecraft, followed by an intense burst of solar protons). The Forbush decrease at the spacecraft was 1.3 ± 0.15 times that at the top of the atmosphere using

extrapolated neutron monitor data. This is attributed to the lower threshold in the spacecraft (75 Mev vs. 2.4 Bev). An energy dependent return to the pre-storm level was noted at the spacecraft. More than 30 days ensued before recovery (neutron monitor data for relativistic particles showed a faster recovery).

Evidently the Forbush decrease "prepared" the interplanetary cavity for the April 1 solar proton event, the transit time being $\geq$ 1 hour. Since the high magnetic field values preceded the solar protons, that is to say, the high values were recorded near earth in the plane normal to the propagation direction at the time of emission of protons, it is safe to say that the solar protons must have been guided by the field. More detailed arguments are given by Coleman, Sonett, and Davis.[76] The cosmic ray data is shown in Fig. 20 and should be compared to Fig. 18 which shows the field changes. It is worth noting that the field normal to the sun was $\sim 50\,\gamma$. Therefore, if the field were primarily radial, say 5^{o} to the solar direction, it would have had to be $\sim 500\,\gamma$, a value high for numerous reasons. Thus we conclude that rotation occurred and the field at the spacecraft had an appreciable angle to the sun. Finally, for a mean energy of, say, 300 Mev, the rectilinear flight time would have been somewhat less than the actual time of one hour, arguing for a curved field.

The solar proton decay law was t^{-1} for the 75 Mev cut-off, whereas for the counter arrangement of Winckler, et al the decay was as $t^{-1.9}$. This would be consistent with a faster decay for the lower energy particle seen by Winckler, et al.[104]

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104. Arnoldy, R. L., R. A. Hoffman, and J. R. Winckler, Solar Cosmic Rays and Soft Radiation Observed at 5,000,000 km from Earth, J. Geophys. Res. 65, 3004 (1960).

F. Summary

In summary, the interplanetary field making a substantial angle with the ecliptic is consistent with some avenues of theory, with the Russian plasma probe data, and with Pioneer V. To complete this necessarily limited and incomplete discussion, it would be necessary to establish the origin of the field seen by Pioneer V. The consequences of the conservation of the angular momentum in a rotating interplanetary field would also require consideration.

During time of solar disturbance, geomagnetic storms and the Forbush decrease have for many years suggested a profound modification of the quiet time field configuration. That this is indeed so is seen by examination of the storm time profile of the Pioneer V magnetometer data which, for each major disturbance during the first month of orbit, also displayed a Forbush decrease

at the spacecraft. Briefly, enhanced fields lying in a plane approximately orthogonal to the earth-sun line were noted rising on one occasion to at least $\sim 50\,\gamma$. The data of March 30 - April 1 is consistent with the model of a large tongue or blast of gas escaping from the sun, transporting outward an extended field and propagating solar cosmic rays as well as occluding the galactic cosmic rays. In some respects, the model suggested is consistent with that of Cocconi, et al[86] and of Gold.[24]

The solar-terrestrial process whose understanding began a century ago with the recognition of solar flares and subsequent magnetic storms now has further experimental verification. Solar emission is observed, the plasma-driven field is seen in space complete with a solar cosmic ray event, and the multitudinous geophysical effects are observed in the magnetosphere and surface of the earth.

Future research in the field of cosmic electrodynamics hinges partially upon the energy availability of large boosters. It does not seem too remote to consider that some one to two decades hence it shall be possible to both approach the sun to something less than 0.1 AU and to escape the solar nebula. Penetration into the galactic arm would permit direct observation of the magnitude of the interstellar field in the neighborhood of the sun. This would permit a direct estimate to be made of the magnetic pressure in the local arm of the galaxy. The relativistic

cosmic ray flux would contribute to the gas pressure. Thus, on the assumption of static equilibrium, the graviational contractive force could be estimated. The isotropy of cosmic rays would determine the leakage rate from the galaxy. The origin of cosmic rays and the processes of acceleration are subjects about which direct evidence could be obtained even with a crude spectrum, for information of this type would determine the rate of production and acceleration of cosmic rays.

Until such time that penetration of the solar-interstellar boundary and direct examination of the magnetic field structure and the relativistic cosmic ray gas in the local arm of our galaxy can be made, rocket technology limits experimental hydromagnetics to a band in the solar system extending from 0.7 AU to 1.2 AU in the plane of the ecliptic.

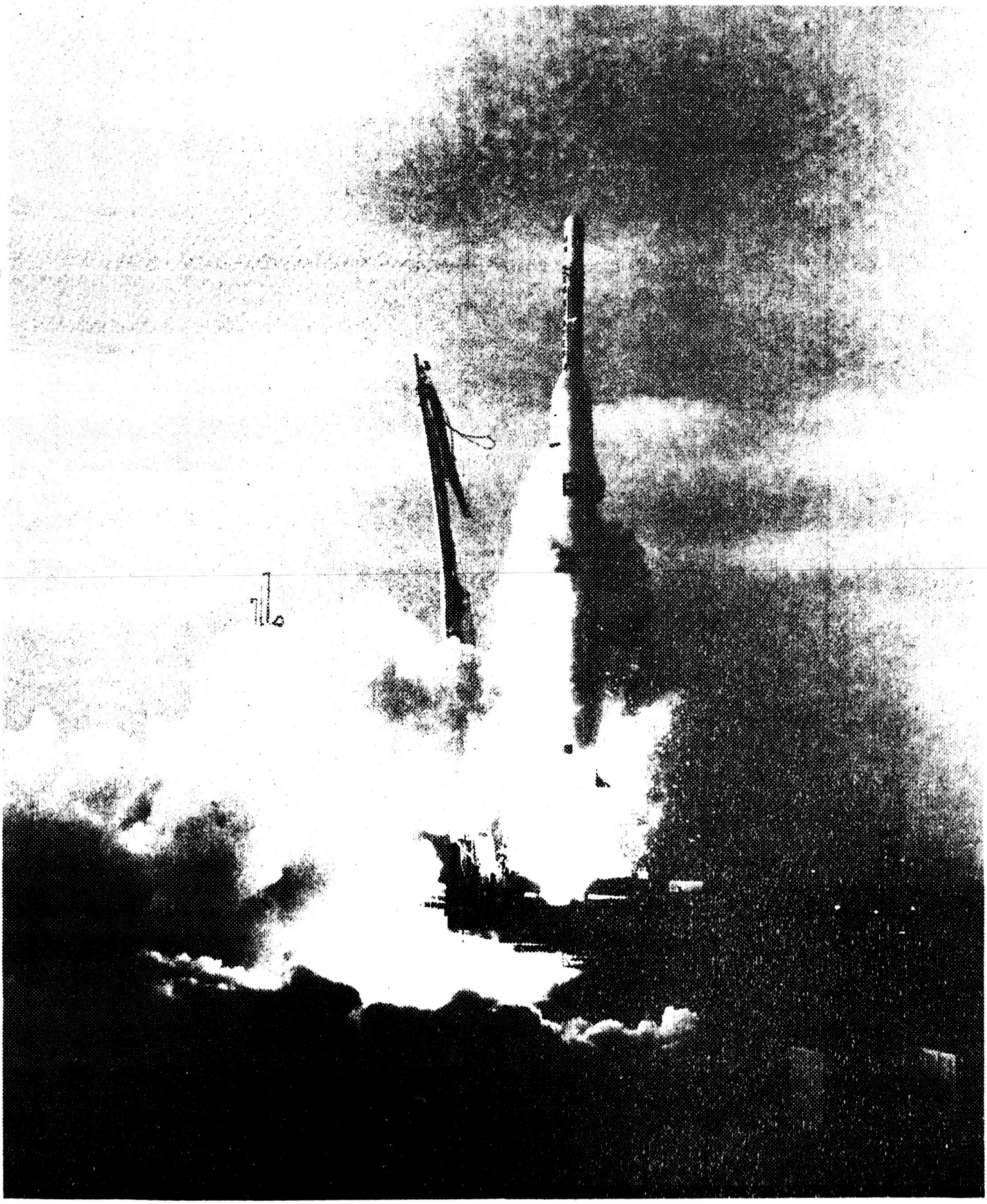
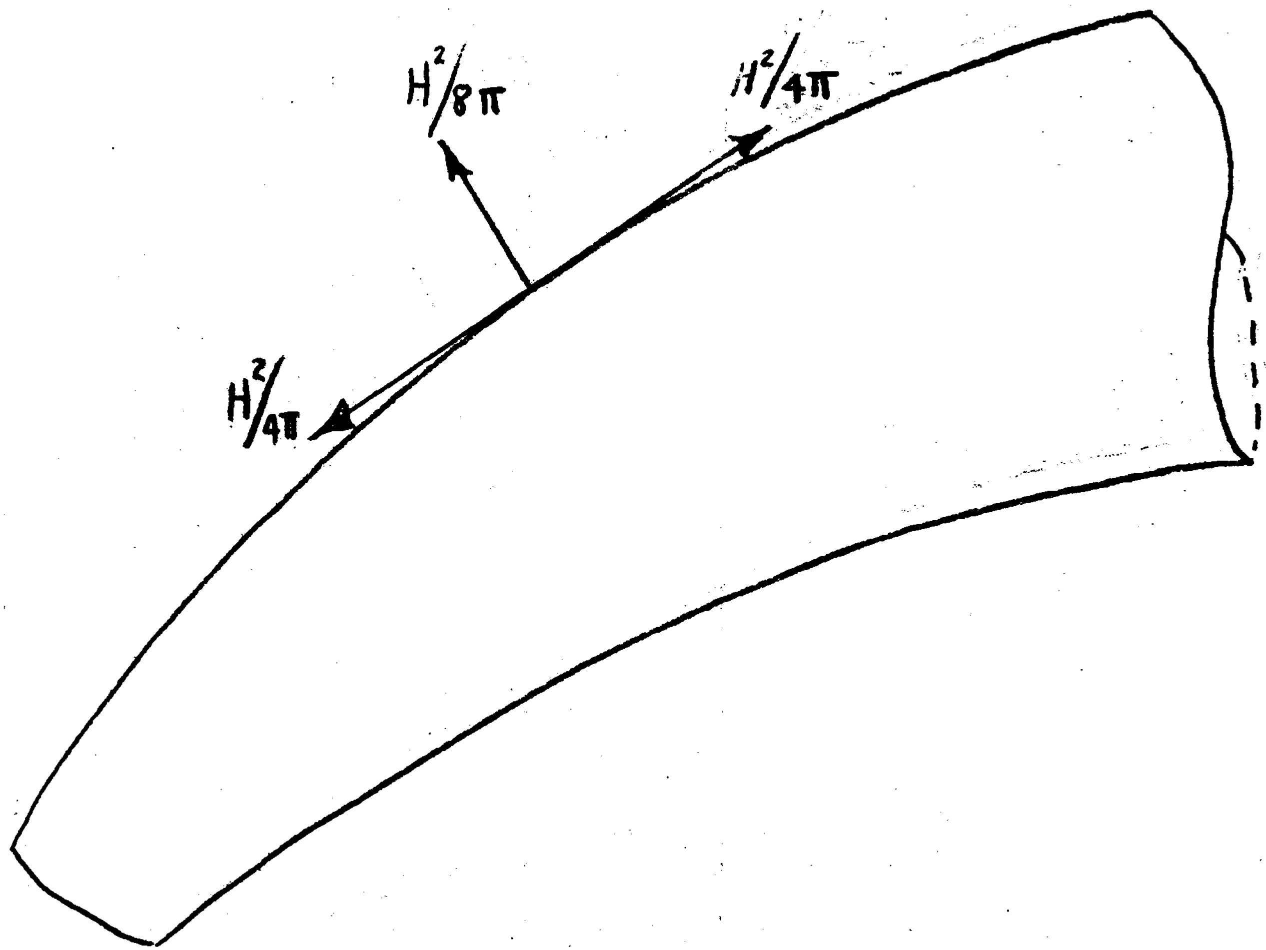


FIG. 1. The launching of Pioneer V on March 11, 1960. This spacecraft achieved the deepest penetration of interplanetary space to this time and provided a number of new scientific observations. (NASA photo)



<u>FIG. 2</u>. Idealized tube of force showing the forces exerted <u>by</u> the <u>field</u>. Plasma forces are not shown.

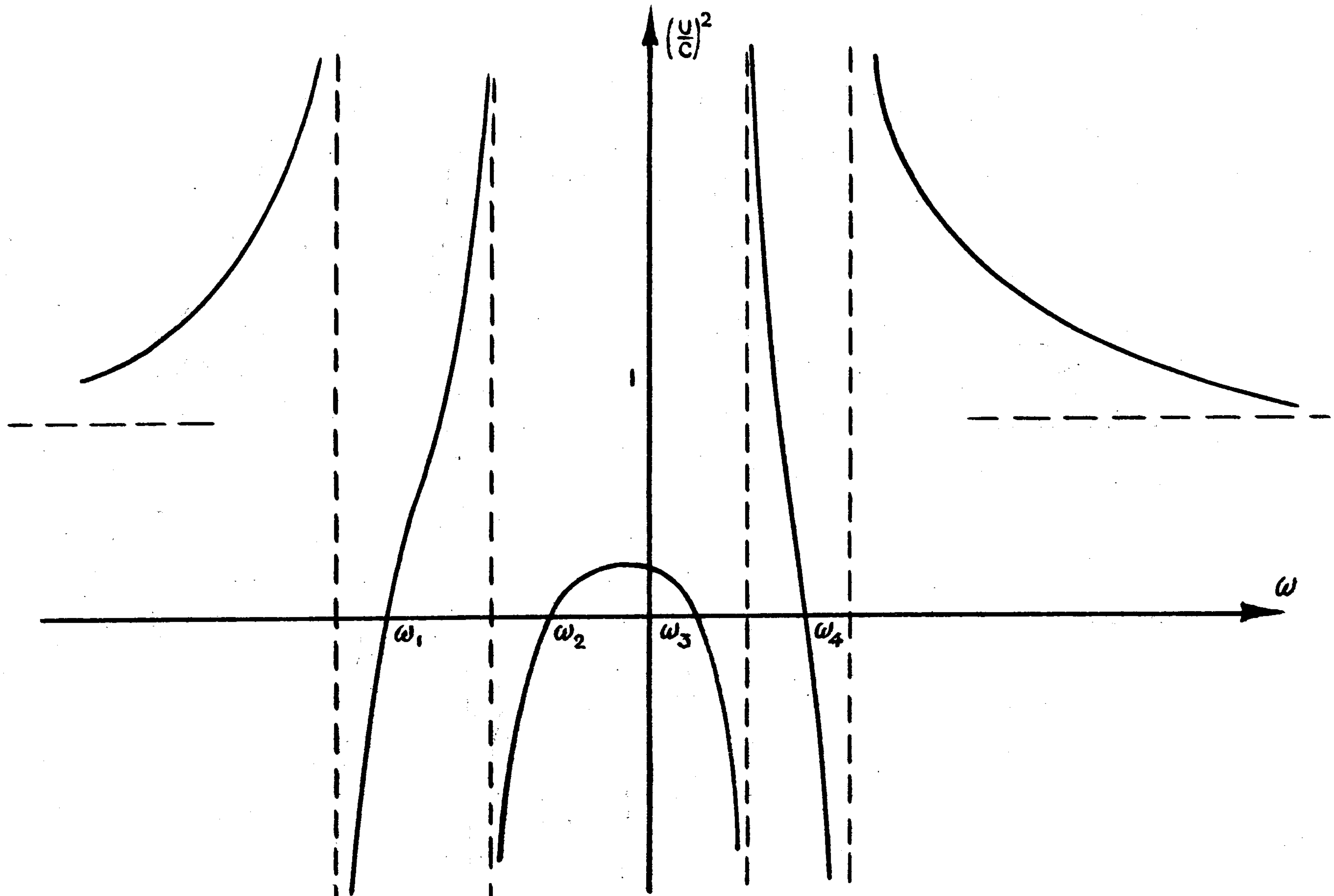


FIG. 3. Passbands and stopbands in a multicomponent gyrotropic plasma for the transverse mode. The vertical asymptotes correspond to the Larmor frequencies, $+\omega$ corresponding to positive particles and $-\omega$ to negative. The lower half-plane corresponds only to evanescent propagation since $(u/c)^2$ 0 where u is the phase velocity. (From Åstrom, E., Ref. 21. Courtesy Archiv. för Fysik.)

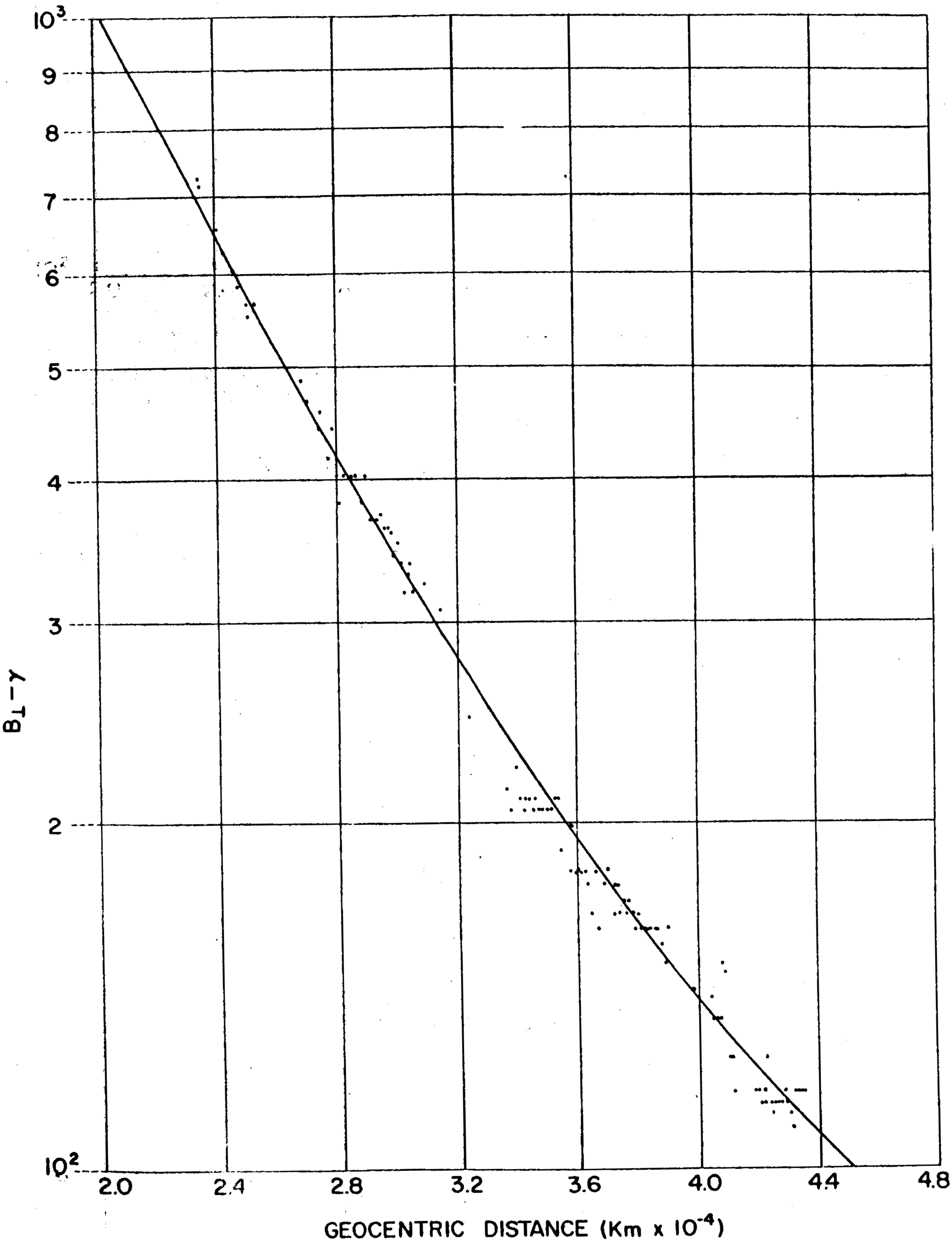


FIG. 4. Radial traverse in the geomagnetic field from $3.7 \leq Re \leq 7$ taken on Pioneer I. (From Sonett, C. P., et al, Ref. 26. Courtesy J. Geophys. Res.)

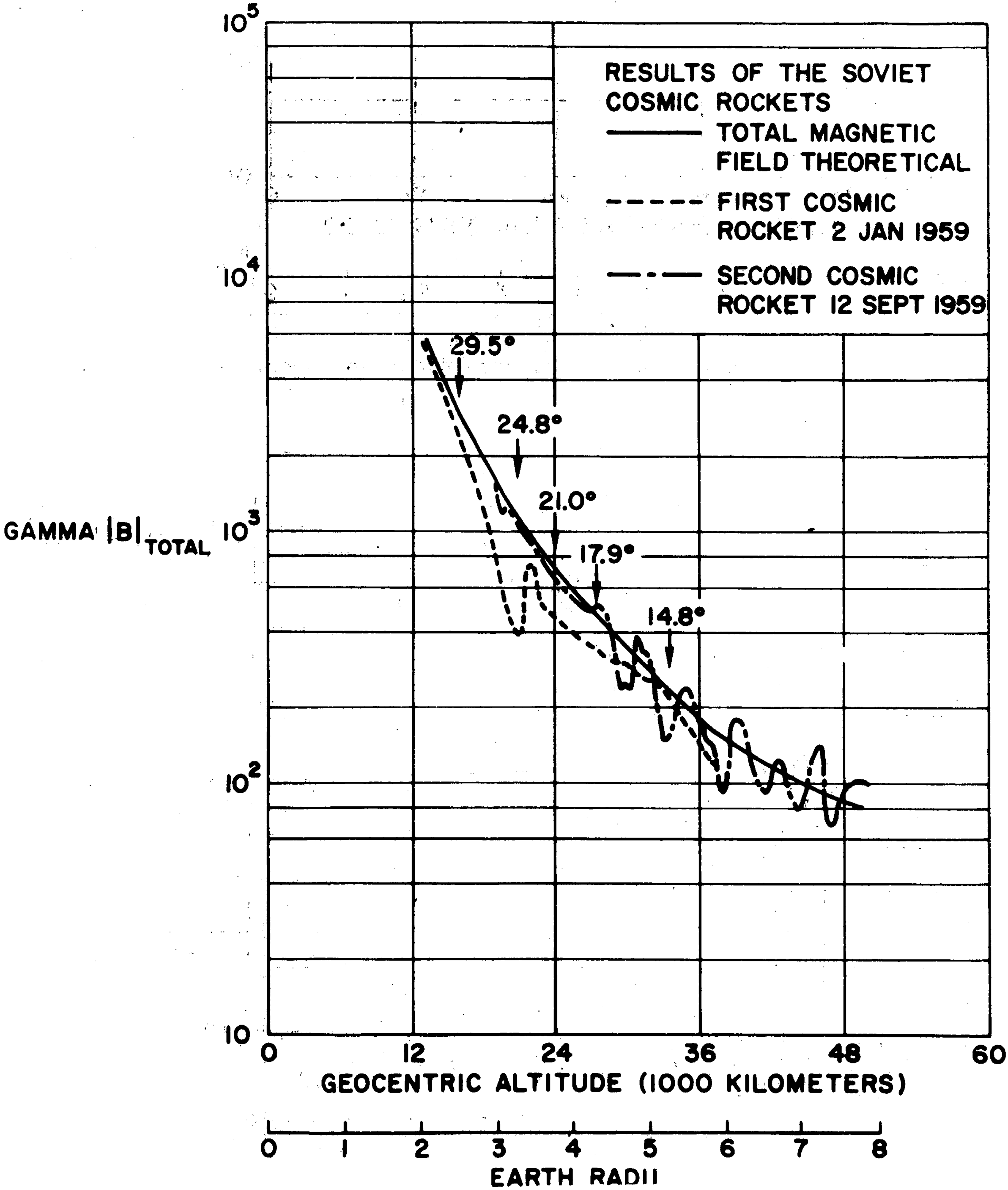


FIG. 5. Radial geomagnetic traverse from Lunik I and Lunik II.

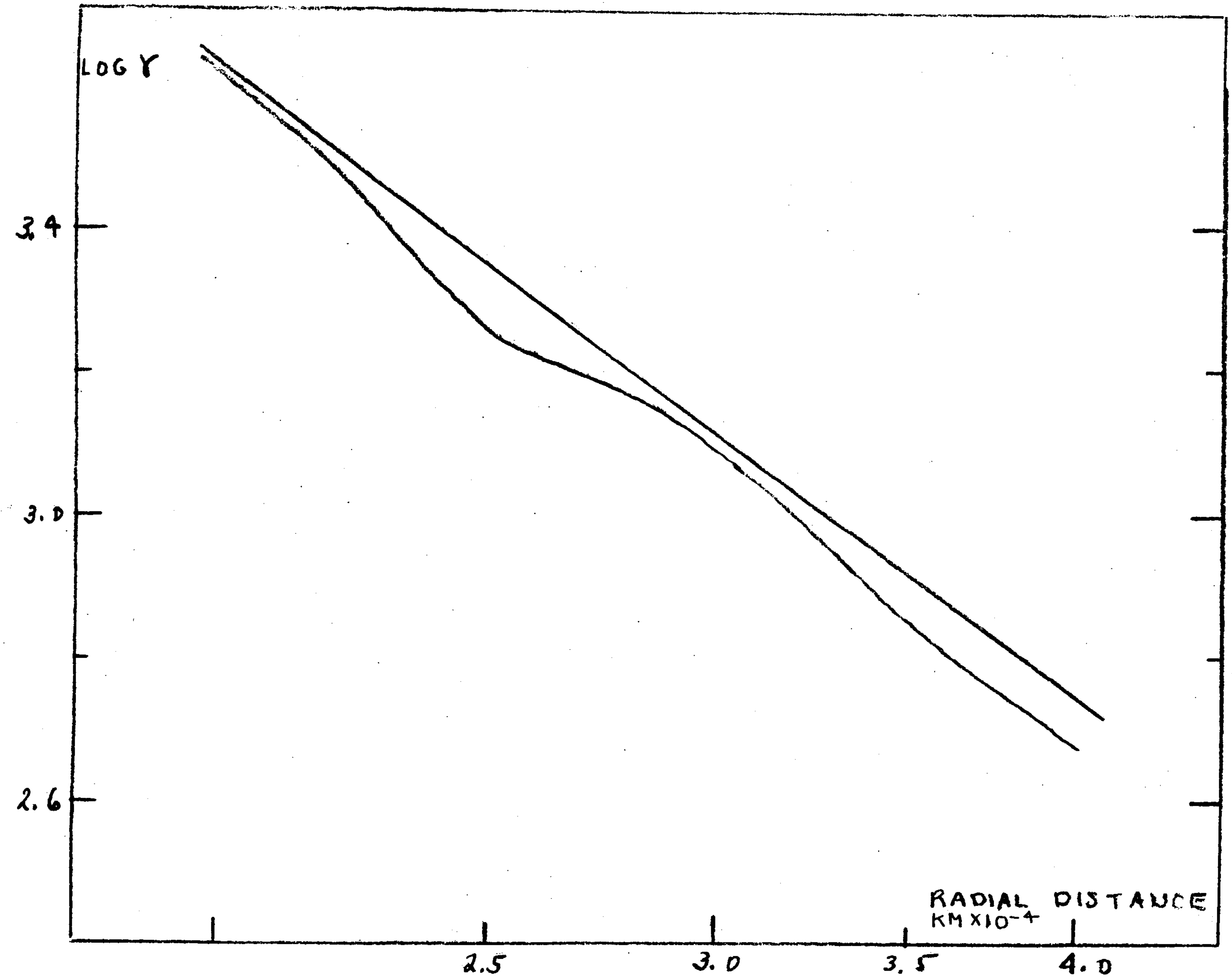


FIG. 6. Theoretical and experimental field from Explorer X in the region of 1.8 to 4 Re showing the non-monotonic character of the field with a minimum at the Van Allen "slot."

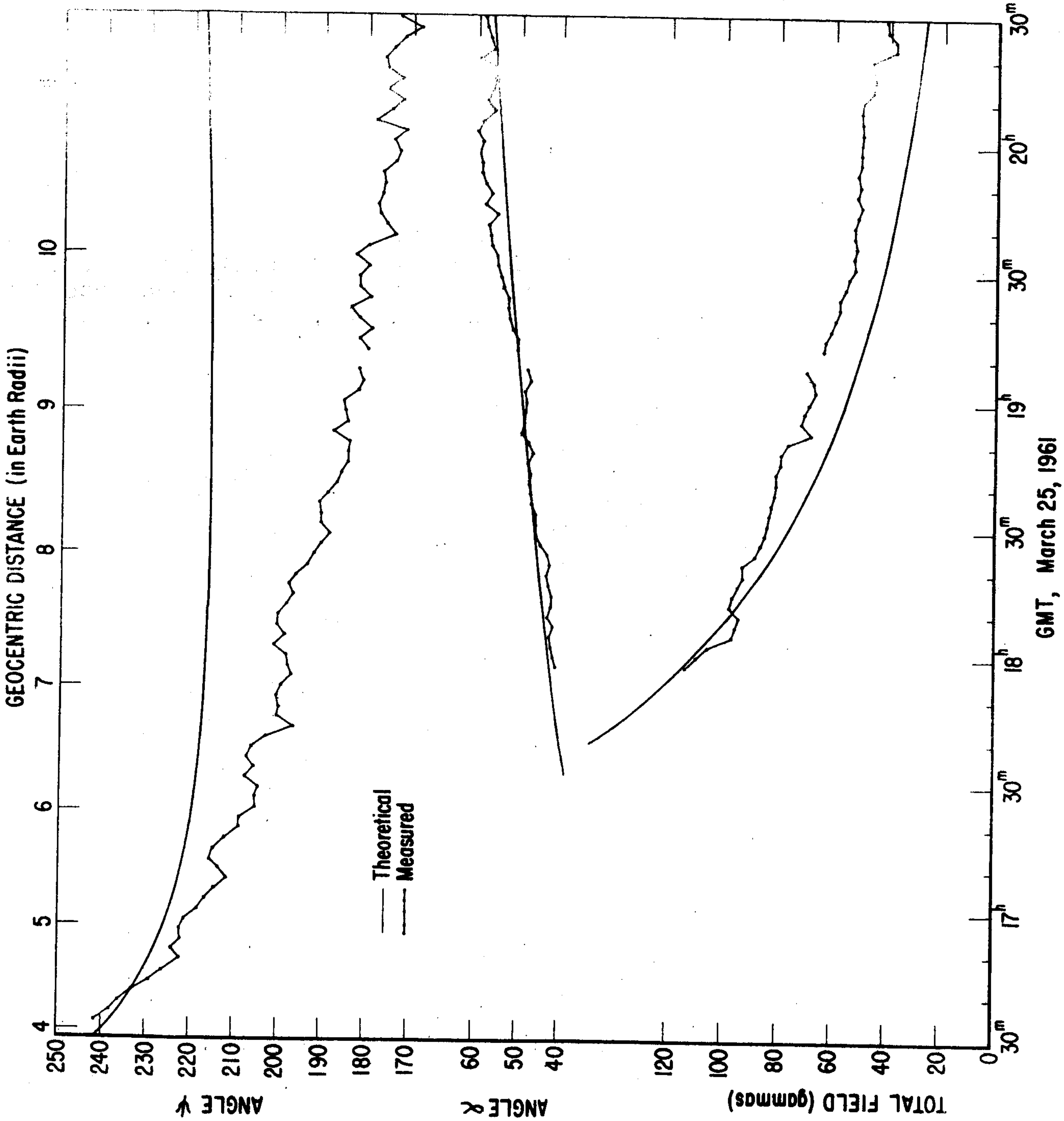


FIG. 7. Data from Explorer X from 4 to 11 Re showing the trend in field magnitude as well as the rotation in direction. The angles are the same as those used in Explorer VI and are defined in the text. (From Heppner, J. P., et al, Ref. 27.)

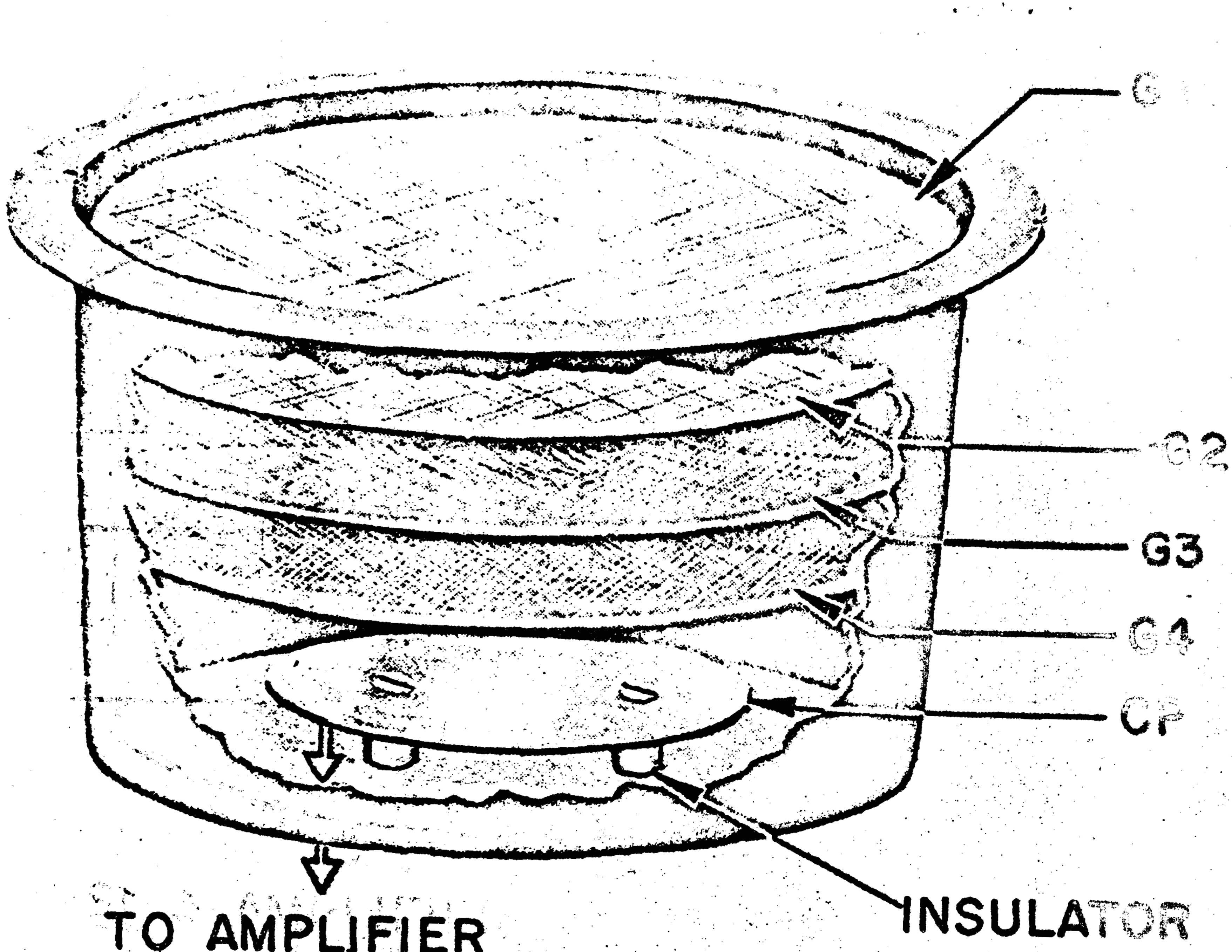


FIG. 8. View of Faraday cup of Bridge, et al, as used on Explorer X. G1 is the ground screen; G2 is a repeller grid to eliminate electrons; G3 is the stepped bias grid; G4 the photoelectric suppression grid; and CP the collector plate.

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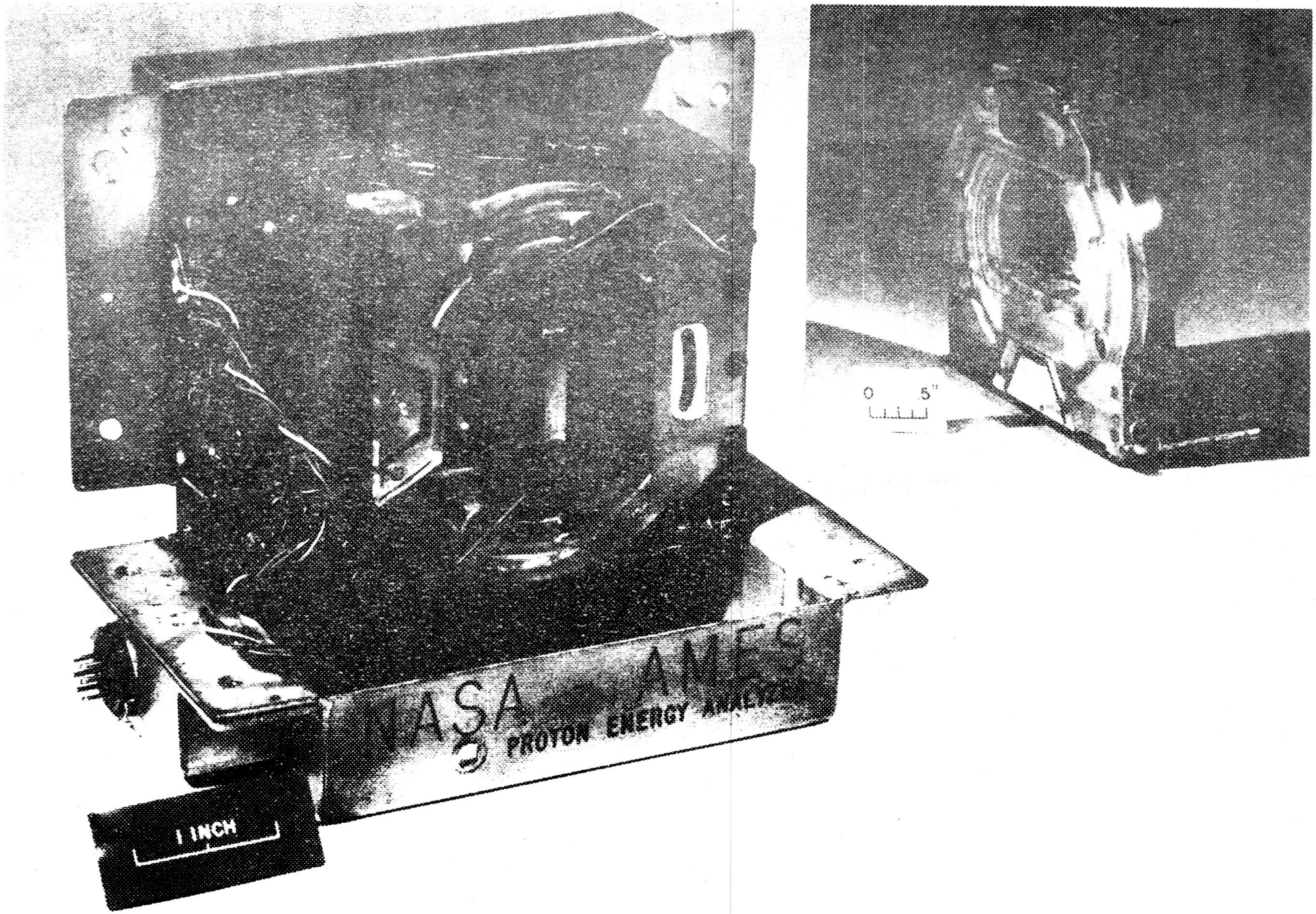


FIG. 9. The differential curved hemisphere electrostatic analyzer of Bader, showing both the geometry and electronics. (NASA photo)

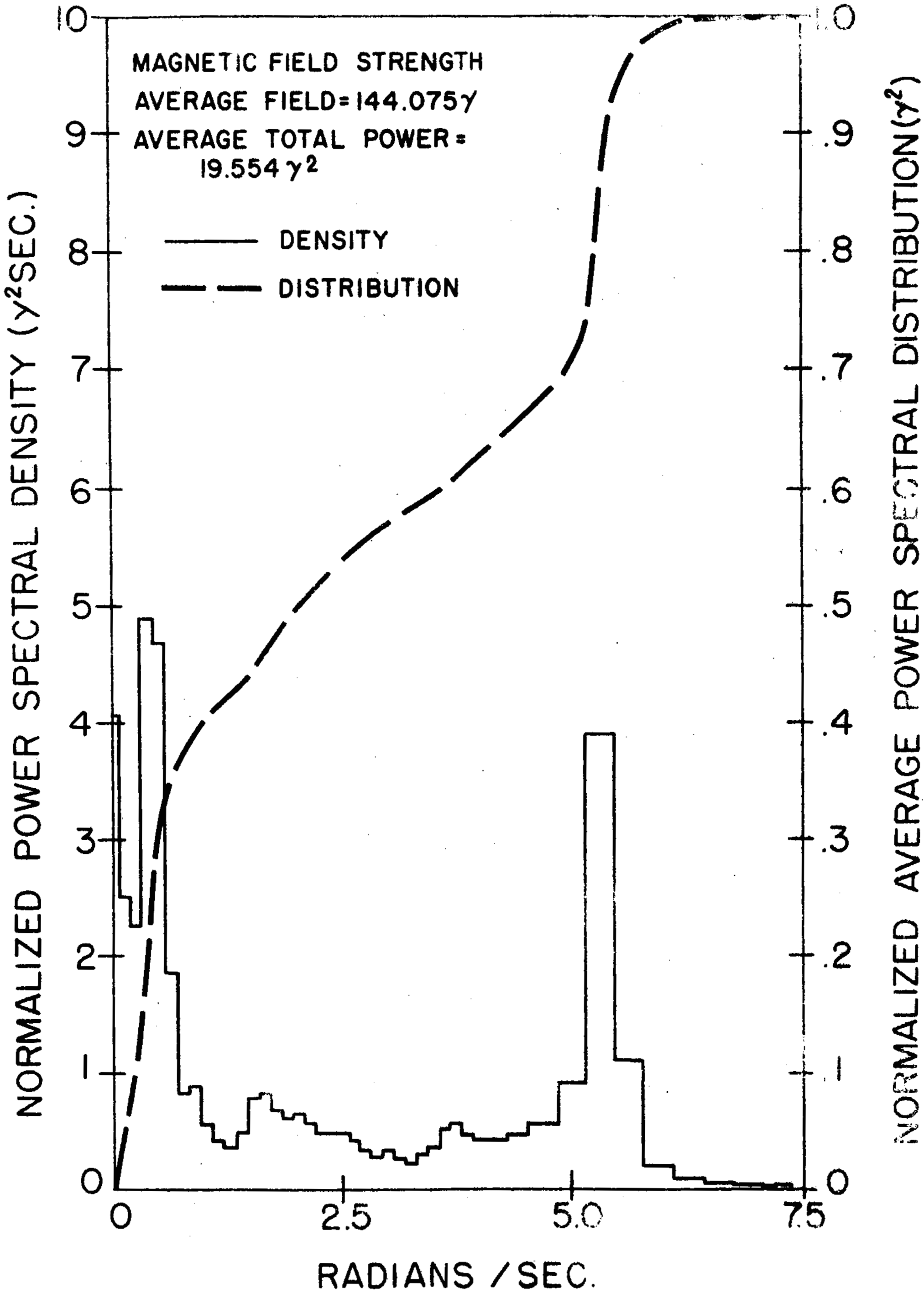


FIG. 10. The differential and integral spectra of hydromagnetic disturbances in the amplitude of the field in the magnetosphere on October 11, 1958. (From Sonett, C. P., et al, Ref. 59. Courtesy J. Geophys. Res.)

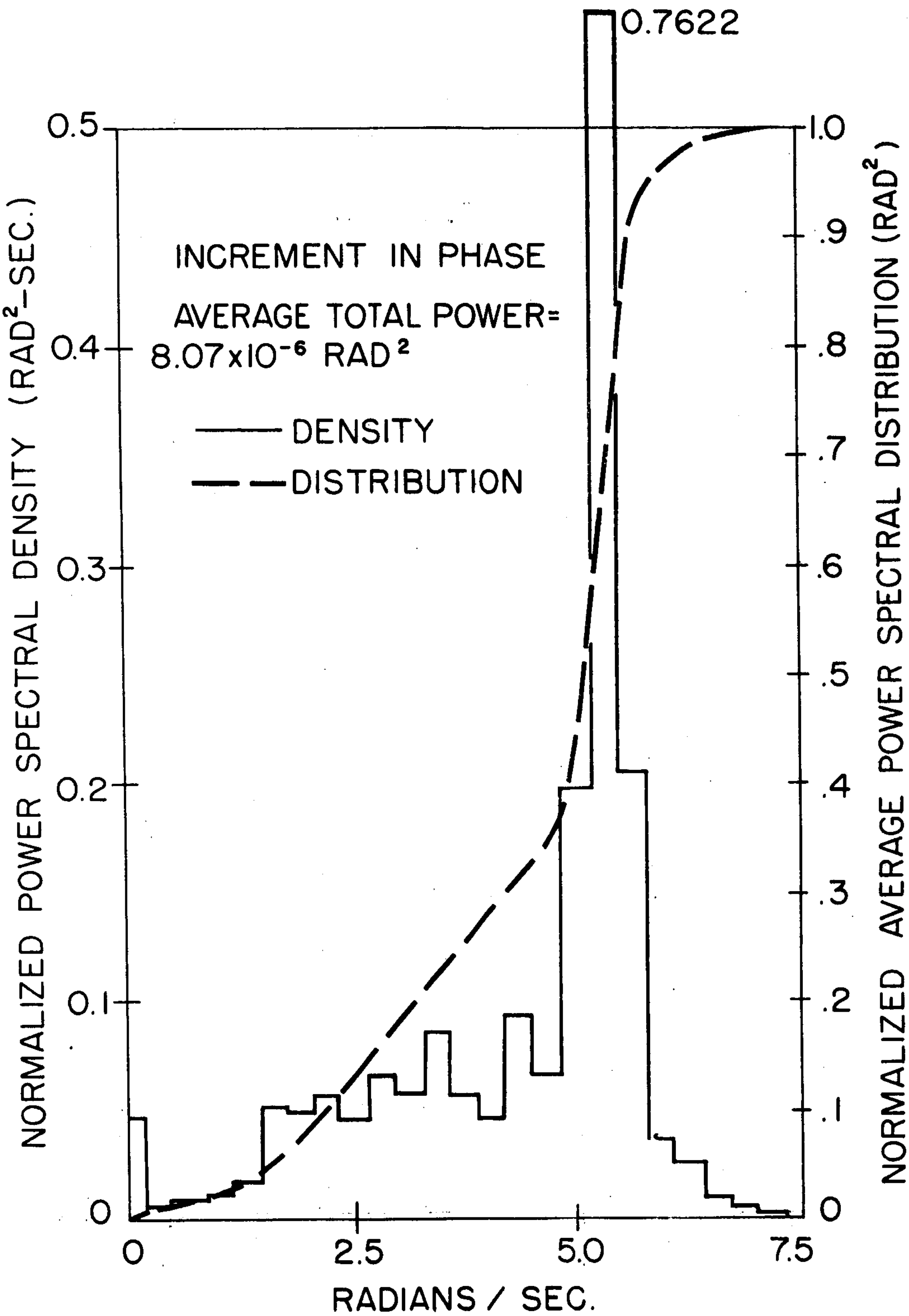


FIG. 11. The differential and integral spectra of transverse disturbances simultaneous with those of Fig. 10. (From Sonett, C. P., et al, Ref. 59. Courtesy J. Geophys. Res.)

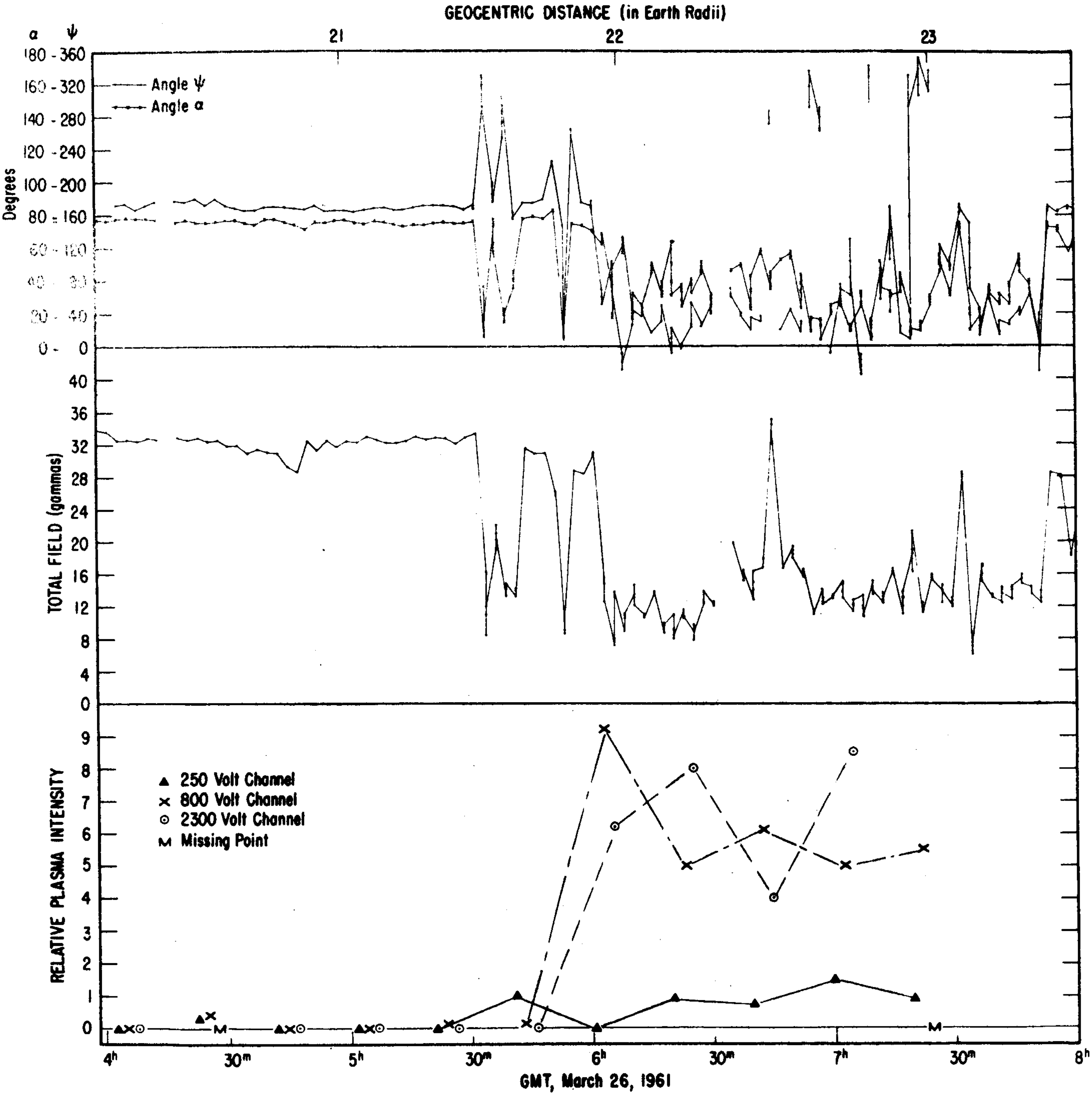


FIG. 12. Apparent termination of the geomagnetic field on the night hemisphere of the magnetopause from Explorer X. This data shows the abrupt transition starting at 21.5 Re concurrent with the appearance of plasma. (From Heppner, J. P., et al, Ref. 27.)

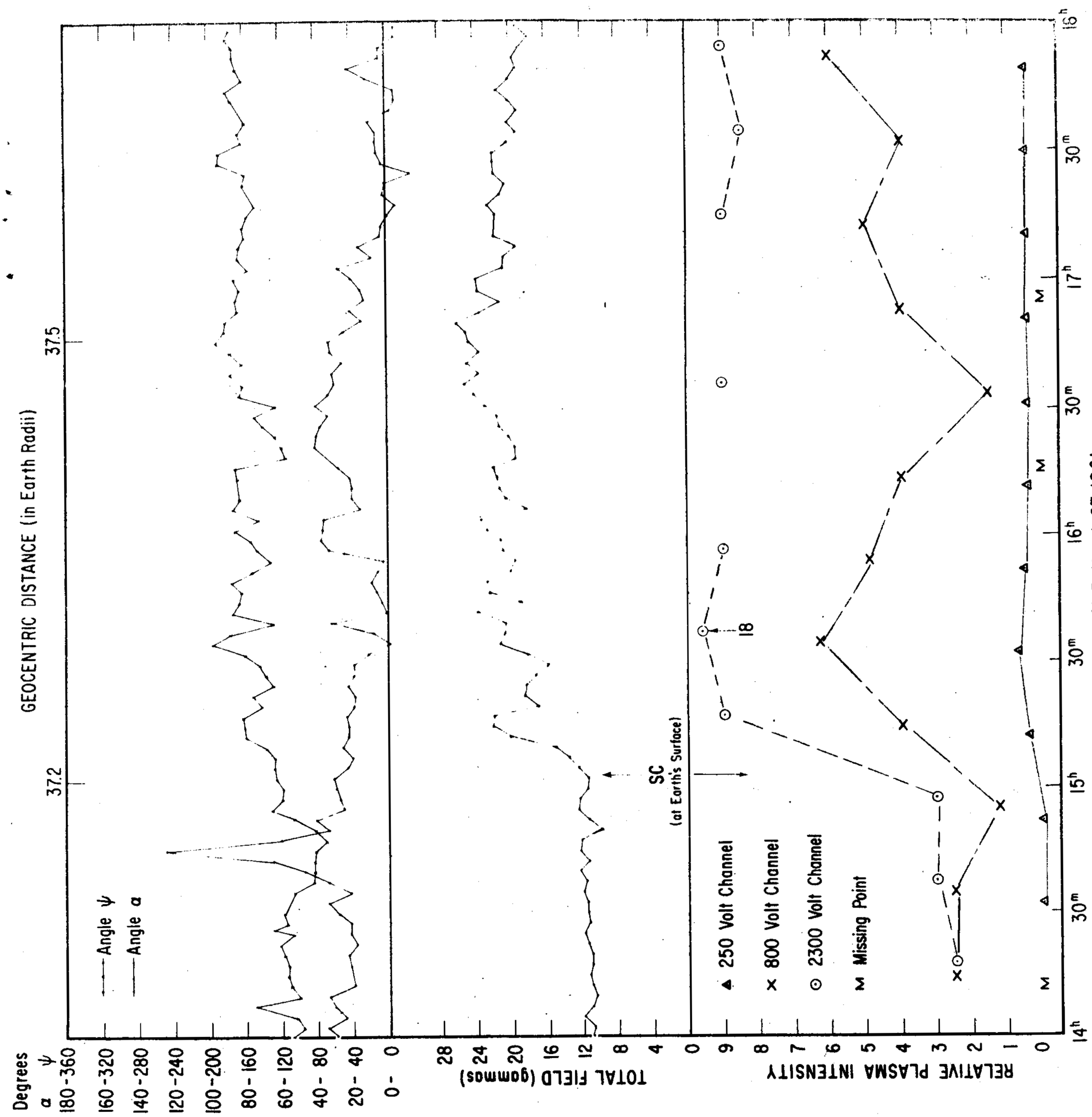


FIG. 13. The occurrence of a sudden commencement magnetic storm at ~37 Re. The field magnitude is not highly disturbed, but a gross rotation occurs, accompanied by a significant change in the plasma flux and spectrum. (From Heppner, J. P., et al, Ref. 27. Courtesy J. Geophys. Res.)

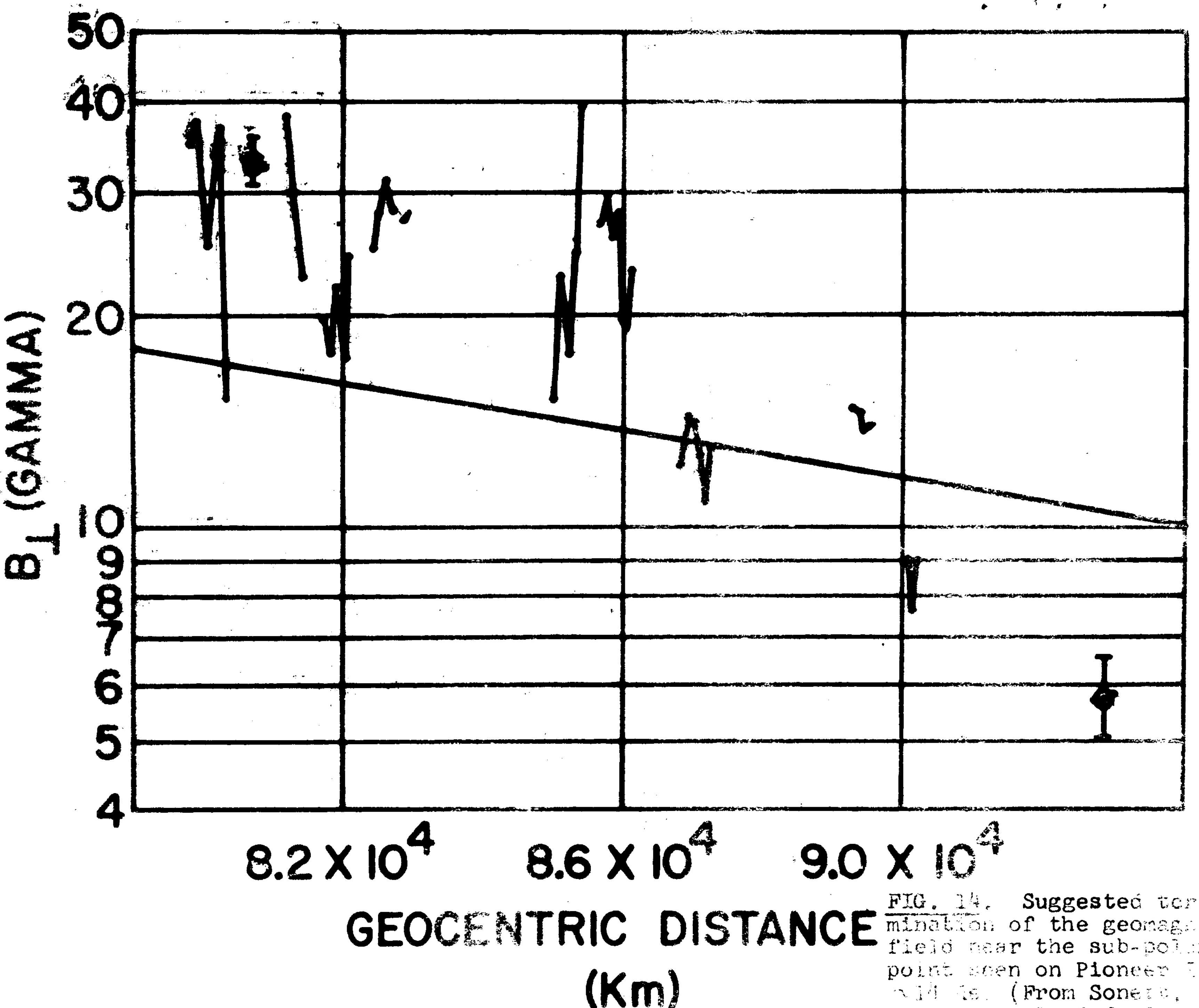
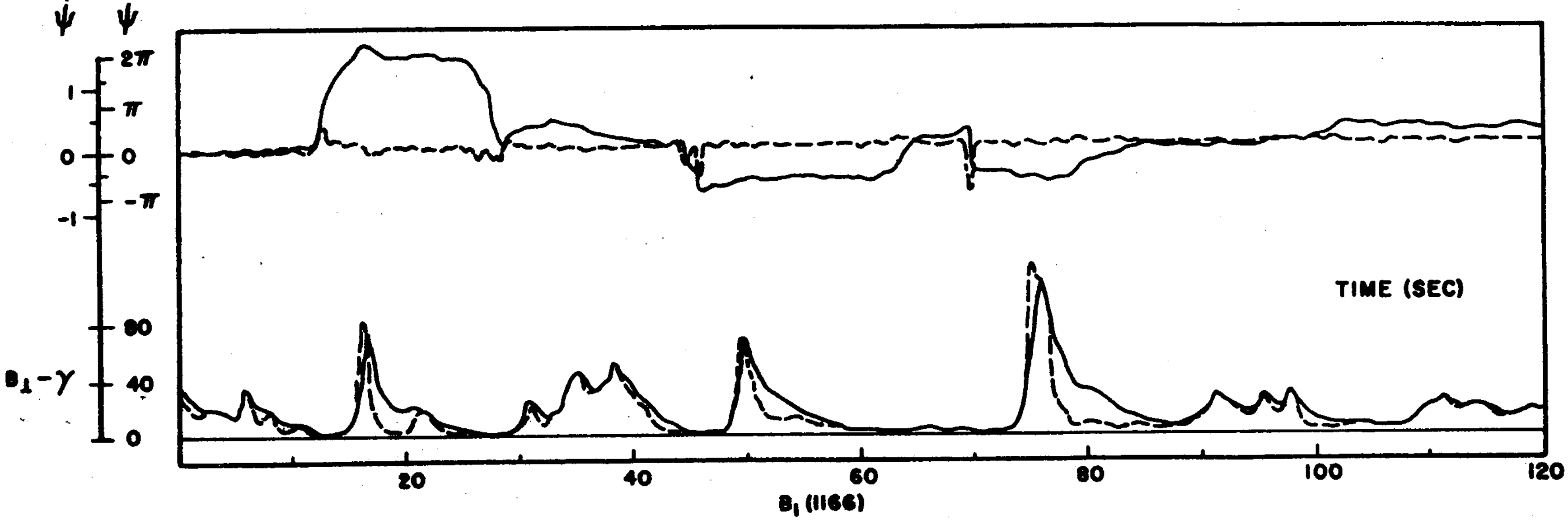


FIG. 14. Suggested termination of the geomagnetic field near the sub-polar point seen on Pioneer [illegible] 14 [illegible]. (From Sonett, C. P., et al, Ref. 20, Courtesy J. Geophys. [illegible]



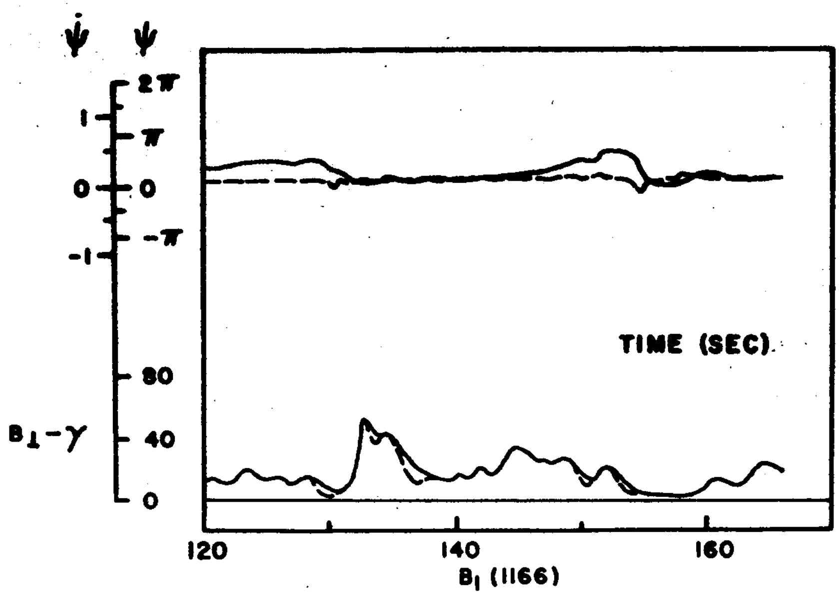


FIG. 15. Fine scale structure of the magnetopause near termination at the sub-solar point, suggesting finite amplitude collisionless waves and X-type nulls. γ shows a number of field rotations through large angle. (From Sonett, C. P., Ref. 82.)

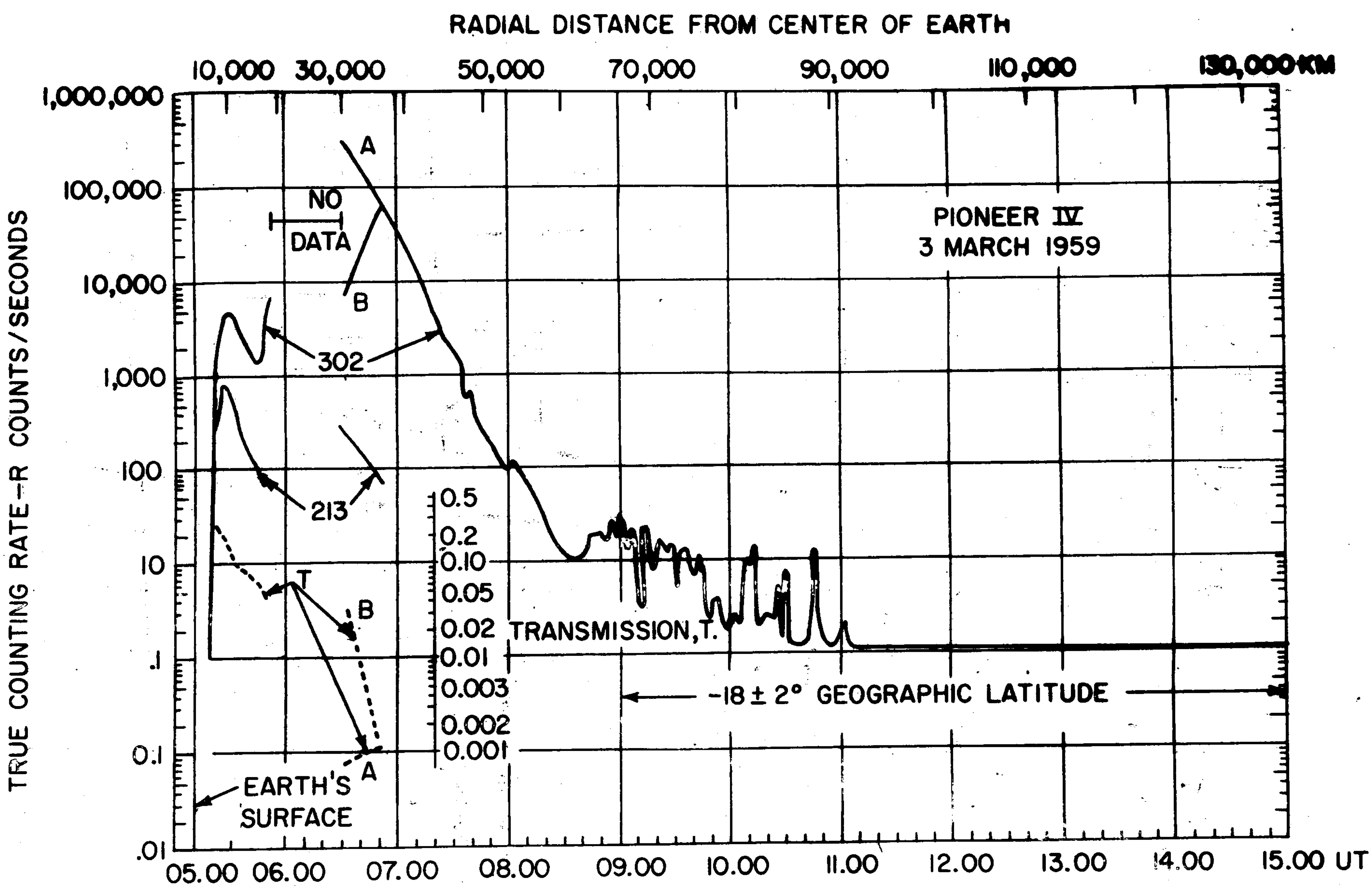


FIG. 16. The sub-solar geomagnetic termination as seen on Pioneer IV, indicating a magnetopause some 4 Re in thickness on this day, and terminating at 14 Re as on Pioneer I. This Figure is a cosmic ray view of the termination. (From Van Allen, J. A. and L. A. Frank, Ref. 83. Courtesy J. Geophys. Res.)

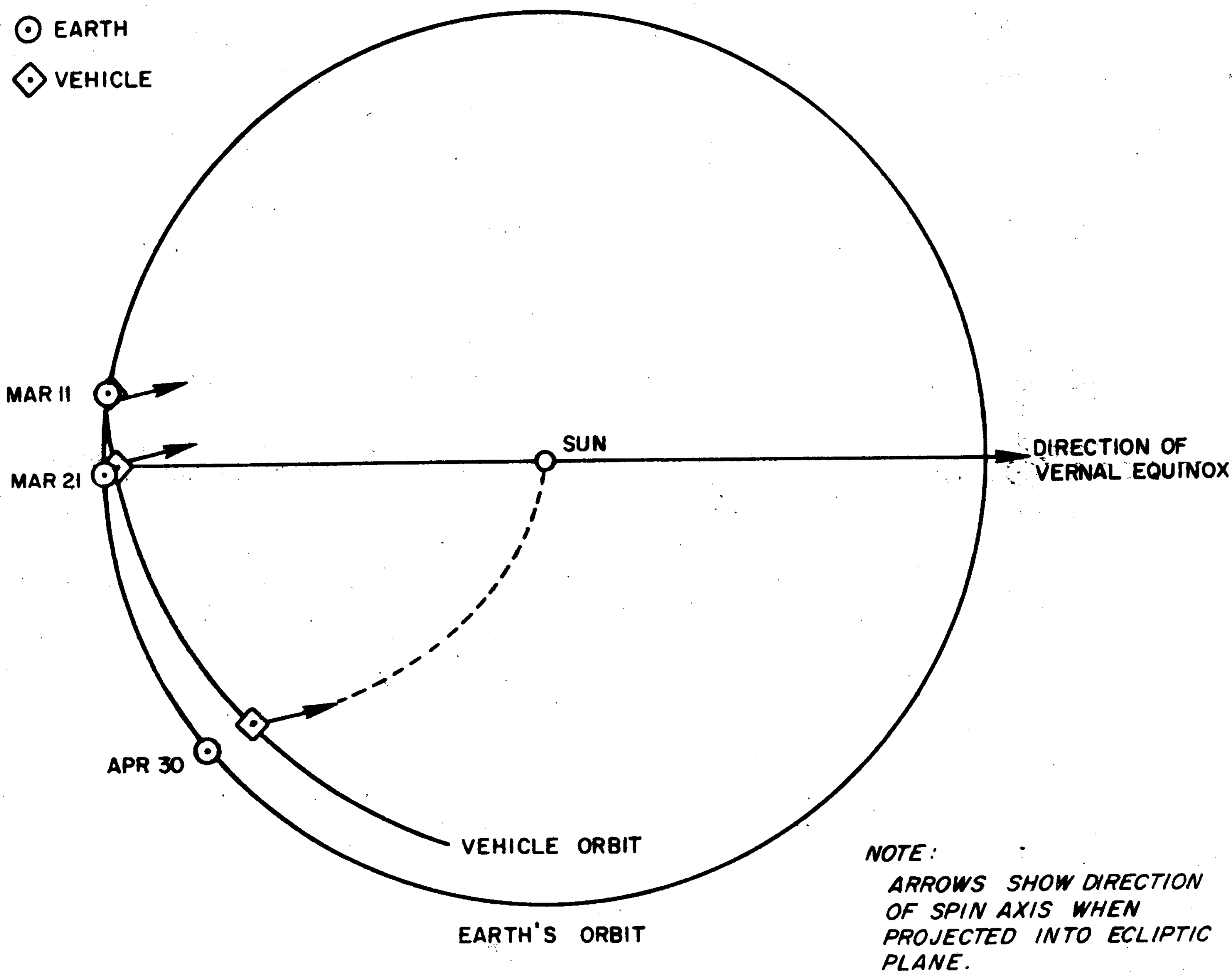


FIG. 17. Orbit of Pioneer V about the sun. The obliquity of the spin axis to the ecliptic (plane of the paper) is 20°. (From Coleman, P. J., et al, Ref. 70. Courtesy J. Geophys. Res.)

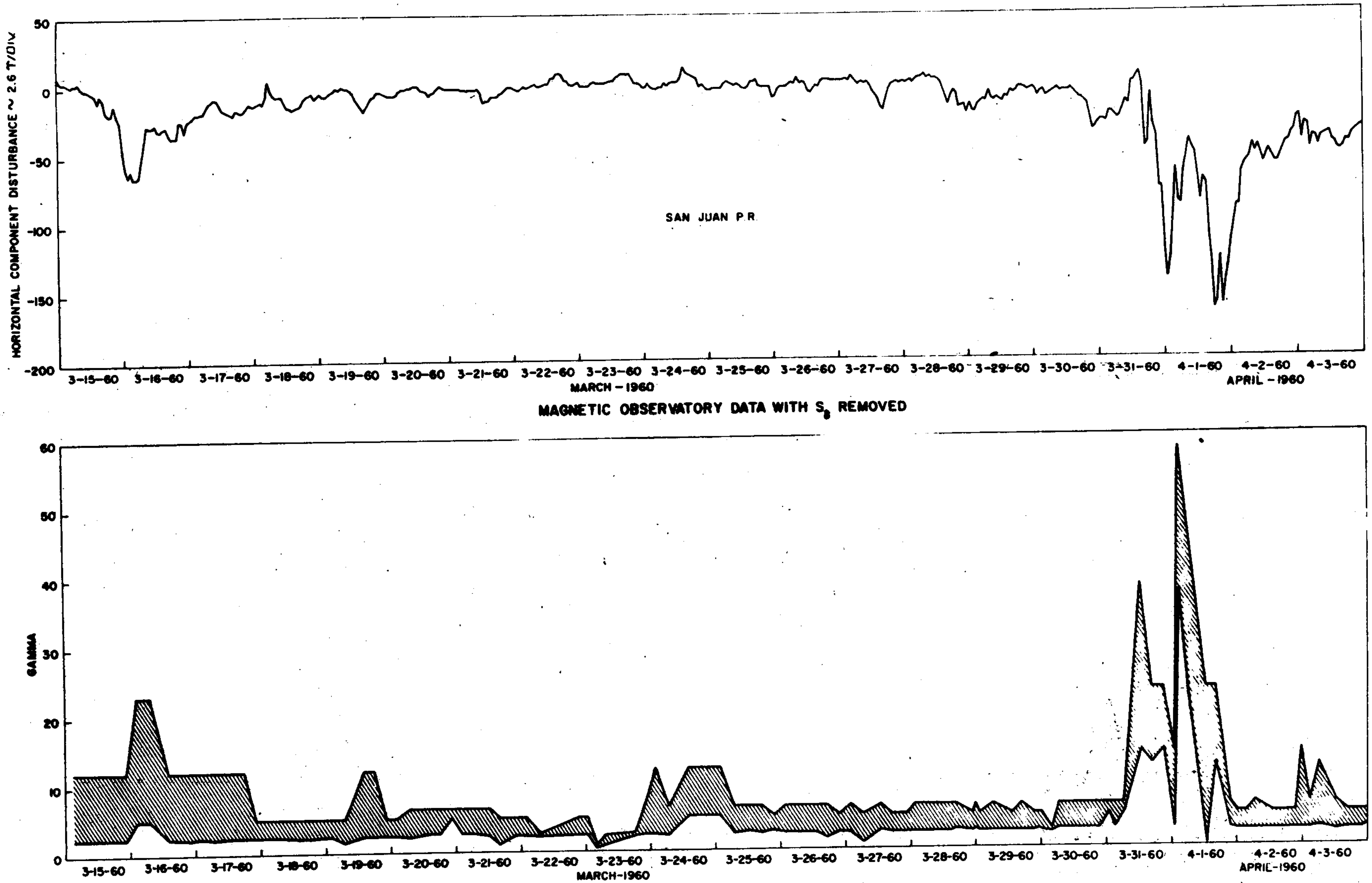


FIG. 18. $\triangle$H at San Juan and field at Pioneer V (0.95 AU on earth-sun line) for three concurrent earth-space disturbances. The space disturbances not seen in $\triangle$H are simultaneous with cosmic ray data of Fan, C. Y., et al, on Pioneer V. The field values are maxima and minima during a particular transmission. (See Fig. 20.) (From Coleman, P. J., et al, Ref. 70. Courtesy Phys. Rev. Lett.)

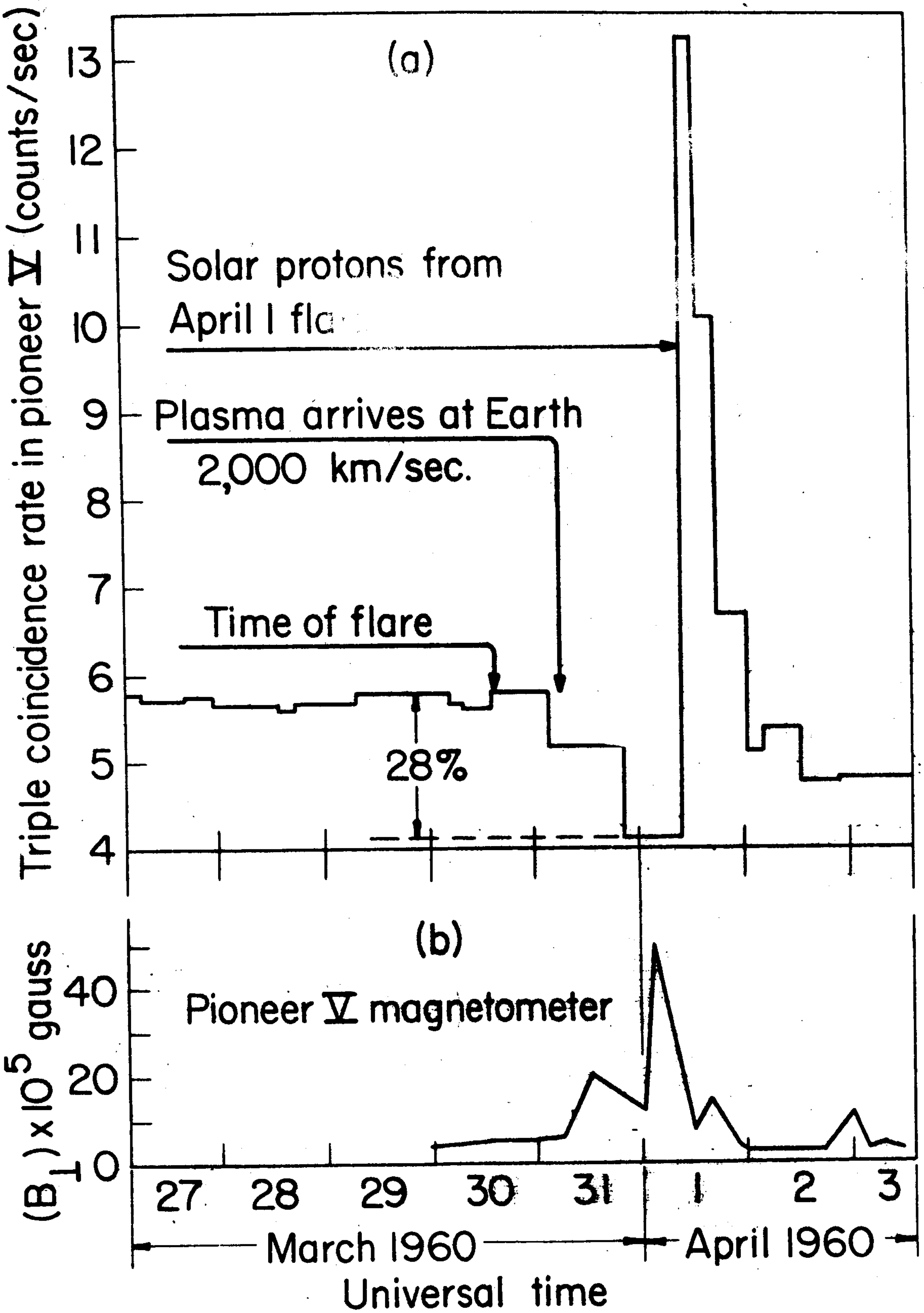


FIG. 19. The detailed timing of events for the interplanetary-geomagnetic storm and solar cosmic ray outburst of March 30-April 1, 1960. (From Fan, C. Y., et al, Ref. 103. Courtesy Phys. Rev. Lett.)

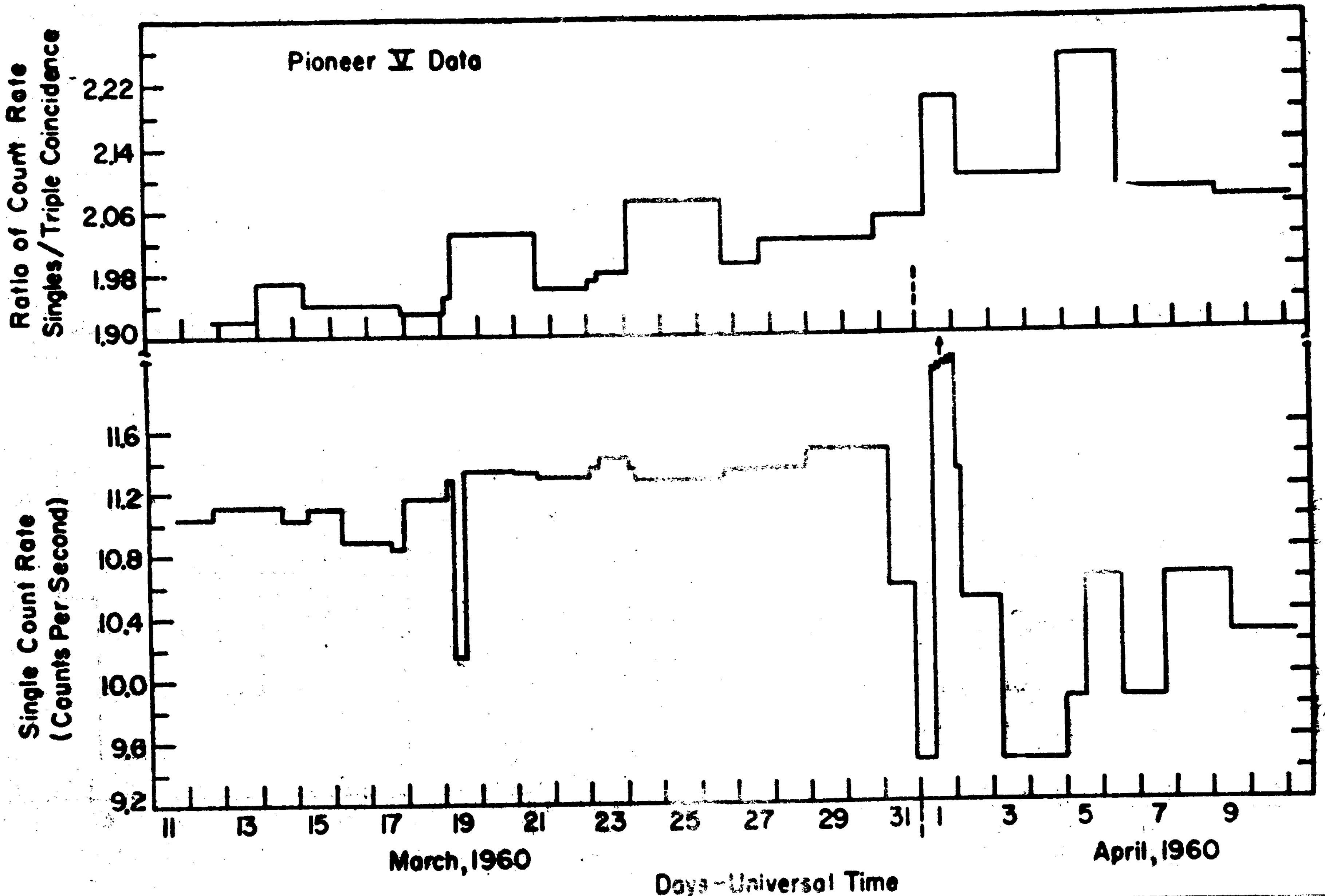


FIG. 20. Cosmic ray data from Pioneer V. The upper plot shows the energy dependence of the Forbush decrease as the singles-triple ratio increases at each magnetic disturbance. (See Fig. 18.) The lower plot shows the singles count alone. Here the statistics are insufficient to show any Forbush effects prior to March 30. The large increase immediately following is a solar cosmic ray event. (From Fan, C. Y., et al, Ref. 103. Courtesy J. Geophys. Res.)

Table I. HIGH SATELLITE AND SPACE PROBE PLASMA DATA (Part One)

NAME	IGY DESIGNATION	LAUNCH DATE	INSTRUMENT
Lunik I (Mechta)		1-2-59	3 electrode trap
Lunik II		9-12-59	4-3 electrode traps
Venus Probe	1961 Gamma	2-12-61	Equipment "similar" to above
Explorer X	1961 Kappa	3-25-61	Faraday Cage
Explorer XII	1961 Epsilon	8-15-61	Curved plate electrostatic analyzer

Table I. HIGH SATELLITE AND SPACE PROBE PLASMA DATA (Part Two)

RANGE	CURRENT RANGE	STATIONARY PLASMAS
Unknown	Unknown	Consistent with Lunik II
Electrons > 200 ev; potentials of -10, -5, 0, +15 volts to spacecraft body.	10^{-10} to 5×10^{-9} amps for ions; 10^{-10} to 1.5×10^{-10} for electrons; threshold $\sim 2 \times 10^{7}$ cm^{-2} sec^{-1}	From $1 < Re < 4.7$ plasma ($T < 5 \times 10^{4}$ °K); beyond 1.5 Re no current on +15 V. trap; neg. currents to 4.7 Re less than 10^{-10} amps; fluctuations from vehicle rotation imply "low" temperature plasma.
By inference one trap biased to +25 volts.		Sporadic between streams; $n_i \leq 1$ cm^{-3} in free space
Automatically programmed stepped bias 0-2300 volts; no provision for negative currents.	5×10^{6} cm^{-2} sec^{-1} of singly charged ions	"Cold" plasma, i.e. ions of velocity comparable to spacecraft velocity from 1.3 to 2.9 Re; density data not available. below threshold from $2.9 \leq Re \leq 21.5$
0.2-20 KV positive ions only	10^{-14} amps or $10^{5} cm^{-2} sec^{-1}$	Not observed to date; data reduction in progress.

Table I. HIGH SATELLITE AND SPACE PROBE PLASMA DATA (Part Three)

STREAMS	REFERENCE
Consistent with Lunik II	K.I. Gringauz, et al (43)
Electron flux $\lesssim 2x10^{8} cm^{-2} sec^{-1}$ at $8.3 < Re < 12.5$	K.I. Gringauz, et al (43)
ion (probably proton) flux $\sim 2x10_{5} cm^{-2} sec^{-1}$; $E > 15$ ev at $3.3x10^{5}$ km $\leq R \leq$ moon impact.	E.R. Mustel (101) K.I. Gringauz & S.M. Rytov (44)
Ion flux $\sim 2x10^{8}$ cm^{-2} sec^{-1} at $R \sim 1.25x10^{5}$ km or $1.5x10^{5}$ km correlated with K index	
ion flux $\sim 10^{9}$ cm^{-2} sec^{-1} (Mustel); $\eta_i \sim 20$ cm^{-3} for $V \sim 500$ km/sec (timed from storm)	
Irregular density streams from solar direction beyond 21.5 Re; mean energy $\sim$ 500 ev shifted higher after SC; indicated velocity $\sim$ 300 km/sec; out of phase correlation with magnetometer amplitude.	H. Bridge, et al (47,48) J.P. Heppner, et al (27)
Occasional bursts of 2-15 KV ions; density mostly 1-10 cm^{-3}; $6x10^{4} \leq Re \leq 8x10^{4}$ km	M. Bader (49,50)

Table II (Part One)

MAGNETOMETER EXPERIMENTS

NAME	DESIGNATION	LAUNCH DATE
Venus Probe	---	2-12-61
Pioneer I	---	10-11-58
Explorer VI	1959 Delta	8-9-59
Pioneer V	1960 Alpha	3-11-60
Vanguard III	1959 Eta	9-18-59
Lunik I	---	1-2-59
Lunik II	---	9-12-59
Explorer X	1961 Kappa	3-25-61
Explorer XII	1961 Epsilon	8-15-61

Table II (Part Two)

MAGNETOMETER EXPERIMENTS

THRESHOLD RANGE	INSTRUMENT
---	variometers
threshold $\lesssim 1\,\gamma$ at bottom of range. range < 1 to $10^4\,\gamma$; non-linear amplifier	search coil
threshold $< 1\,\gamma$ at bottom of range. range < 1 to $3 \times 10^3\,\gamma$; non-linear amplifier; angle threshold $\sim 1^o$	search coil sun scanner
threshold $< 0.5\,\gamma$; sensitivity determined by digitization windows $0.05\,\gamma$ to $5\,\gamma$ depending on window and log response of amplifier	search coil
threshold ~ 0.1 gauss; accuracy at least $1:10^5$ determined in part by ground oscillator reference	proton precession magnetometer
quoted threshold $\sim 100\,\gamma$; may be due to spacecraft fields	field-aligned flux gates
quoted threshold $\sim 50\,\gamma$; may be due to spacecraft fields	field-aligned flux gates
Rb magnetometer accuracy determined by orbit data; still being considered. Flux gates calib. by Rb; self-consistent shift of $7\,\gamma$	Rb magnetometer flux gates sun scanner
may be dependent on digitization windows whose width ~ 20	flux gates

Table II (Part Three)

MAGNETOMETER EXPERIMENTS

RANGE	REFERENCE
---	Mustel, E. R. (101)
3.7 - 7 Re 12.6 - 14.3 Re	Sonett, et al (26, 28)
1 - 8 Re	Sonett, et al (32) Smith, et al (38)
0.9 - 1.0 AU	Coleman, et al (69, 70)
---	Heppner, et al (27)
lunar impact	Dolginov & Pushkov (33)
lunar impact	Dolginov & Pushkov (33)
1 - 37.5 Re	Heppner, et al (27)
~ 1 - 8 Re	Cahill (40)

Table III. COSMIC RAY DETECTORS ON PIONEER V

DEVICE	SHIELDING	GEOMETRY	REMARKS
Triple coincidence telescope	1 gm/cm^2 brass counter walls; 5 gms/cm^2 Pb	$\sim 2\pi$	triples threshold $\sim$75 Mev for protons; $\sim$13 Mev for electrons; counter dead time $\sim$0.5 μsec. Filling methane-argon
Geiger tube	$\sim$1 gm/cm^2	$\sim 4\pi$	halogen filled Auton 302
Ionization chamber	$\sim$1 gm/cm^2	4π	argon filled; Neher-Millikan quartz fiber

NOTE: None of the shielding values are accurate, since the spacecraft data has not been published; the addition of absorber from the body of the spacecraft is probably not serious for the 75 Mev threshold and tends to increase the bremmstrahlung yield for the singles events in the telescope. For the Geiger tube and ion chamber the effects may be substantial; some idea may be gained by reference to the Explorer VI case (Hoffman, R. H., R. L. Arnoldy, and J. R. Winckler, J. Geophys. Research 67, 1 (1962).